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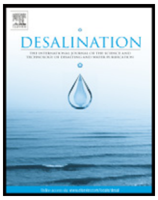

Energy-efficient reverse osmosis desalination: Effect of retentate recycle and pump and energy recovery device efficiencies

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HIGHLIGHTS

- EERO is a hybrid of SSRO and CMCR for high recovery seawater desalination.
- EERO gives lower osmotic pressure differential at all recoveries relative to SSRO.
- EERO gives lower SEC beyond the critical overall recovery relative to SSRO.
- Increasing recovery of terminal RO stage in the 3-stage EERO can reduce the net SEC.
- Including non-ideal pump and ERD efficiency favors the EERO relative to SSRO.

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ABSTRACT

The development of commercial RO membranes offering high salt rejection and flux has focused more attention on improving desalination process technology. The energy-efficient reverse osmosis (EERO) process has recently been advanced that combines single-stage reverse osmosis (SSRO) with a countercurrent membrane cascade with recycle (CMCR). The SSRO retentate is the feed to the CMCR that employs countercurrent retentate and permeate flow, permeate recycle, and retentate self-recycling via the use of NF membranes in one or more stages. This reduces the foulant load on the RO stage in the CMCR and allows it to run at a higher recovery than conventional SSRO. This option as well as the effects of pump and energy-recovery device (ERD) efficiencies are considered here. For a typical 35 g/L seawater feed and 0.35 g/L water product, the 4-stage EERO process reduces the osmotic pressure differential (OPD) relative to conventional SSRO by 50% at all overall water recoveries. For pump and ERD efficiencies of 85% and 90%, respectively, the 3-stage EERO process has a 50% overall water recovery at an OPD of 42.7 bar and a net specific energy consumption (SEC_{net}) of 2.323 kWh/m^3, thereby reducing the OPD by 23.1% at the cost of increasing the SEC_{net} by only 3.6% relative to conventional SSRO. For the same efficiencies the 4-stage EERO process can achieve a 75% overall water recovery at an OPD of 55.5 bar and SEC_{net} of 3.773 kWh/m^3, thereby reducing the OPD by 50% and the SEC_{net} by 3.6% relative to conventional SSRO at that recovery.

1. Introduction

Reverse osmosis (RO) technology is a pivotal method for desalination. The global applications of RO technology for seawater desalination are projected to grow from a capacity of 40 to 100 million m^3 per day from 2008 to 2015 [1]. However, the RO process is known to be relatively energy-intensive and system optimization can further reduce RO energy consumption. In particular, energy is required for the pumps that supply the pressure to overcome the membrane resistance, osmotic pressure, concentration polarization and flow through the channels. Furthermore, membrane fouling requires increasing the pressure to maintain constant water production. Owing to the advances in material science and engineering, commercially available RO membranes now offer high rejection while having a very low membrane resistance [2–4], thereby permitting much enhanced fluxes, subject to increased polarization control. Thus, further improvements in desalination will need to focus more on process optimization and control strategies to reduce the overall energy consumption [5–7], and increase product recovery. The benefit of improved recovery is the more effective use of the process pretreatment stage, although attention has to be paid to control of scale formers.

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In a recent paper Chong et al. [8] introduced the novel energy-efficient reverse osmosis (EERO) process that combines single-stage reverse osmosis (SSRO) with either a 2-stage or 3-stage countercurrent membrane cascade with recycle (CMCR) to increase the water recovery while reducing osmotic pressure differential (OPD), which is the osmotic pressure difference across the membrane between the brine and permeate, at an acceptable specific energy consumption (SEC). Chong et al. [8] discussed in detail the limitations with respect to increasing the water recovery of conventional SSRO, a commonly used process configuration for desalination, two SSRO stages in series, which is typically used for water reclamation to achieve high recovery, and just a CMCR. A brief summary of their discussion is provided here. In SSRO the global minimum SEC occurs when water recovery is at 50% i.e. for a typical 35 g/L seawater feed and 0.35 g/L water product, the OPD is 55.5 bar and the minimum net SEC is 1.54 kWh/m^3 with an ideal pump and 100% efficiency energy-recovery device (ERD). However, when the water recovery is increased to 75%, the OPD increases significantly to 111 bar and net SEC becomes 3.08 kWh/m^3. When two SSRO stages in series are used in which the retentate from stage 1 serves as the feed to stage 2, a booster pump is required for additional recovery from stage 2. For an overall recovery of 75%, the 2-stage in series process has the same OPD value as SSRO but a substantially lower net SEC of 2.06 kWh/m^3. Without using an interstage booster pump, the net SEC would be similar to a SSRO. It should be noted that operating the RO system at 111 bar is impractical as there is a maximum pressure delivered by a conventional seawater RO pump or handled by a RO membrane, which is typically 69 bar (or the higher pressure type of up to 80 bar) [9,10]. Therefore, conventional seawater desalination has not been designed to operate at high recovery due to the pressure limitation. On the other hand, a CMCR can be employed to increase the water recovery; it can achieve an overall water recovery of 75% at 55.5 bar, which represents a 50% reduction in the OPD relative to conventional SSRO; however, this comes with a penalty in net SEC of 4.87 kWh/m^3 owing to the increase in pumping requirement for re-pressurizing the permeate recycle.

This brief overview suggests that an optimal desalination process would combine the benefits of conventional SSRO with a CMCR, which is the novel EERO process discussed in this paper. The features of EERO include (i) coupling of SSRO with a CMCR; (ii) countercurrent retentate and permeate flow; (iii) permeate recycling; and (iv) retentate self-recycling owing to the use of one or more nanofiltration stages. The objective of EERO is to achieve high water recovery (i.e. >50%) at lower OPD and at an acceptable SEC (i.e. $SEC_{EERO}/SEC_{SSRO} < 1$ at the same recovery level) where the SSRO process is used as a baseline for comparison. Chong et al. [8] showed that for a 75% overall water recovery, for a 3-stage EERO, the net SEC and OPD are 2.74 kWh/m^3 and 74 bar, respectively, that represent reductions of 11% in the SEC and 33% in the OPD relative to conventional SSRO; whereas the 4-stage EERO has a net SEC of 3.08 kWh/m^3 (same as SSRO) and OPD of 55.5 bar that represents a 50% reduction relative to conventional SSRO.

Chong et al. [8] mentioned that increasing the recovery in the terminal stage of the EERO process could potentially improve its efficiency; however, they did not explore this option. The maximum water recovery in each stage was limited to 50% in order to ensure a safety factor of one to minimize membrane fouling. In addition, Chong et al. [8] commented that incorporating non-ideal pump and energy recovery device (ERD) efficiencies would favor the EERO process since it achieves the same recovery at a lower operating pressure relative to SSRO; however, they did not explore this in detail. In this paper the effect on the performance of the EERO process of having a higher recovery in the terminal stage of the EERO process and employing non-ideal pump and ERD efficiencies will be explored. Section 2 provides an analysis of the 3-stage EERO process that incorporates variable recovery in the terminal stage, variable pump efficiency, and variable ERD efficiency; Section 3 provides the same analysis for the 4-stage EERO process; Section 4 presents and discusses the results of the analysis; and Section 5 gives a summary of the results and conclusions drawn from this study.

2. Analysis of the 3-stage EERO process

2.1. Description of the 3-stage EERO process

The 3-stage EERO process shown in Fig. 1 consists of an SSRO stage whose retentate is the feed to a countercurrent membrane cascade with recycle (CMCR) that employs an NF membrane in stage 1 and RO membrane in stage 2. The combined permeate from the SSRO stage and stage 2 provides the potable water product. This novel process configuration can decrease the osmotic pressure differential (OPD) and increase the overall water recovery at reduced net specific energy consumption (SEC_{net}) at the cost of only a slight increase in the membrane area relative to conventional SSRO. The manner in which the EERO process can accomplish this will first be explained, after which the process will be analyzed.

The EERO process capitalizes on the reasonable recovery and relatively low SEC_{net} of SSRO by employing it as the primary stage. It uses multiple stages to increase the recovery by sending the retentate from the SSRO as the feed to a CMCR. Series-staging in conventional SSRO requires interstage high pressure pumping owing to the increase in salt concentration. However, optimal design of the EERO process obviates the need for interstage pumping on the retentate side. The EERO process employs both permeate recycle to the retentate side of the CMCR and retentate 'self-recycling' to the permeate side of the CMCR that occurs because the NF membrane in stage 1 passes some salt to the permeate side. The combination of countercurrent retentate and permeate flow and permeate recycling and retentate self-recycling enables the CMCR to augment the overall recovery without an increase in OPD. Optimal operation of the EERO process corresponds to avoiding an entropy-of-mixing penalty at the mixing point, which requires operating the SSRO and CMCR stages at the same OPD. Conventional SSRO is usually run at a safety factor (ratio of the retentate to permeate flow in stage i) $\chi_i \geq 1$ to avoid scaling that dictates the allowable stage recovery Y_i, since they are interrelated by $Y_i = 1/(1+\chi_i)$. However, since the divalent salts that cause scaling are substantially removed in the NF stage, it is possible that stage 2 in the 3-stage EERO process can be operated at a higher recovery than would normally be used for RO. This potential advantage of the EERO process is explored in this paper. The 3-stage EERO process requires an additional high pressure pump to recycle the permeate from stage 2 to stage 1. The effect of the efficiency of the high pressure pumps on SEC_{net} is explored in this paper. The retentate brine product from the EERO process is more concentrated and at a lower pressure than that from conventional SSRO. The effect on the SEC_{net} of the efficiency of the energy-recovery device (ERD) that can be used to recover the mechanical pressure energy in this brine is also explored in this paper. The osmotic potential energy in the brine from the EERO process can be twice as concentrated as that from conventional SSRO at the same operating pressure i.e. at 55.5 bar, the 4-stage EERO can achieve recovery of 75% as compared to recovery of 50% in SSRO [8]. As such, it can be used to significantly increase the energy density in the pressure-retarded osmosis (PRO) process for harvesting this energy.

2.2. Solution to describing equations

Chong et al. [8] analyzed the 3-stage EERO process assuming the recovery in each CMCR stage was 50% and the pumps and ERD were 100% efficient. In the present analysis these assumptions are relaxed. This analysis also determines the retentate recycle ratio required to increase the safety factor in any stage for which the recovery is increased beyond 50%.

The equations describing the performance of the 3-stage EERO process are solved analytically to obtain explicit equations for the overall