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Effect of Stream Mixing on RO Energy Cost Minimization

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ABSTRACT

Various mixing operations between the feed, retentate and permeate streams are studied in this work to determine their effectiveness in decreasing the specific energy consumption (SEC) of single-stage (single-pass), two-pass and two-stage reverse osmosis (RO) processes operated at the limit of the thermodynamic restriction. The results show that in a single-stage RO process, partial retentate recycling to the feed stream does not change the SEC, while partial permeate recycling to the feed stream increases the SEC if targeting the same overall water recovery. Energy optimization of two-pass membrane desalination, with second-pass retentate recycling to the first-pass feed stream and operated at the limit imposed by the thermodynamic restriction, revealed the existence of a critical water recovery. When desalting is accomplished at recoveries above the critical water recovery, two-pass desalination with recycling is always less efficient than single-pass desalination. When desalting is accomplished at recoveries below the critical water recovery, an operational sub-domain exists in which the SEC for a two-pass process with recycling can be lower than for a single-pass counterpart, when the latter is not operated at its globally optimal state. For the two-stage RO process, diverting part of the raw feed to the second stage, in order to dilute the feed to the second-stage RO, does not decrease the minimal achievable SEC of a two-stage RO process. The various mixing approaches, while may provide certain operational or system design advantages (e.g., with respect to achieving target salt rejection for certain solutes or flux balancing), do not provide an advantage from an energy usage perspective.

1. Introduction

Energy cost remains one of the most important factors contributing to the cost of water desalination via reverse osmosis (RO) processes [1–3]. The introduction of highly permeable RO membranes has led to a significant reduction in the energy consumption in RO desalination [4,5]. As a result, the feasible operating pressure for the new generation of high permeability membranes is approaching the limit imposed by the thermodynamic restriction [6,7]. This constraint specifies that the feed-side pressure cannot be lower than the sum of the osmotic pressure of the exit brine stream and pressure losses (in the membrane channel) in order to ensure that permeate product water is produced along the entire membrane surface area [9]. As argued in a previous study [8], significant reduction in the cost of RO water desalination is less likely to arise from the development of significantly more permeable membranes, but it is more likely to arise from: (a) optimization of process configuration [9,11], (b) implementation of advanced control schemes (e.g., to account for feed salinity fluctuation [10] and even temporal fluctuation of electrical energy purchasing price), (c) utilization of low cost renewable energy sources, and (d) more effective and lower cost feed pretreatment and brine management strategies [12].

Recent studies have demonstrated that when a membrane desalting process can be operated up to the limit imposed by the thermodynamic restriction, there is an optimal product water recovery at which the specific energy consumption (i.e., energy consumption per volume of permeate produced) is minimized [9]. For example, the optimization model was successfully demonstrated in a recent study showing significant energy savings (up to 22%) under fluctuating feed salinity (up to 43%) [10]. It has been shown, via a formal optimization procedure, that the optimal operating condition shifts to higher recovery with increased membrane and brine management costs [9]. It has also been suggested that the energy consumption for membrane desalting would decrease with increased number of desalting stages where inter-stage pumps are utilized.

More recently, a two-pass membrane desalination process was evaluated and compared to a single-pass process when both processes operate at the limit of the thermodynamic restriction [11]. Considerations of energy recovery, pump efficiency and the limitations imposed by membrane rejection level have led to the conclusion that a single-pass process is more energy efficient relative to a two-pass process.

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However, in our previous works [8,9,11], the impact of various stream mixing and recycling configurations on the SEC of an RO plant was not systematically studied.

Extending previous studies on RO optimization for operation at the thermodynamic limit, this work evaluates the effect of possible mixing/blending of various streams (feed, retentate, permeate) on the specific energy consumption (SEC) of RO desalination. To address this problem, the analysis begins with the simplest configuration: single-stage RO desalination, in which two possible recycling (partial retentate recycling and partial permeate recycling) operations are examined. Based on the results from the single-stage RO configuration, two-pass and two-stage desalting with recycling are then studied to determine the effect of various mixing/blending operations on the resulting SEC.

2. Effect of partial recycling operation on the SEC of single-stage RO desalting at the thermodynamic limit

For single-stage RO desalting, full recycling of either the retentate or permeate streams is not possible for a continuous process operation. Therefore, in this section only partial recycling is studied. In the partial retentate recycling operation, part of the retentate stream is diverted to the feed stream immediately before the RO module (Fig. 1(a)), while in the partial permeate recycling operation, part of the permeate stream is diverted to the raw feed (Fig. 1(b)).

2.1. Partial retentate recycling in single-stage RO desalting

For single-stage RO desalting with partial retentate recycling as shown in Fig. 1(a), one can show, via a salt mass balance, that the brine–permeate osmotic pressure difference is $\Delta\pi_{\text{brine}} = \frac{\pi_0 R}{1-Y}$ (π_0: feed osmotic pressure, R: salt rejection, $Y\left(=\frac{Q_P}{Q_{raw}}\right)$: overall water recovery where Q_P is the product water flow rate and Q_{raw} is the raw feed water flow rate), assuming linear relationship between the osmotic pressure and salt concentration [13]. When desalting at the limit of the thermodynamic restriction and neglecting the pressure drop in the system [9], the feed pressure is given by:

$$\Delta P = P_F - P_0 = \Delta\pi_{\text{brine}} = \frac{\pi_0 R}{1-Y} \tag{1}$$

Since the recycled retentate stream of a pressure P_F is fed directly into the inlet of the RO unit, there is no additional pump work involved to pressurize it to P_F; thus, the rate of pump work for the RO system in Fig. 1(a) is given by:

$$\dot{W} = \Delta P \times Q_{raw} = \frac{\pi_0 R}{1-Y} Q_{raw} \tag{2}$$

Therefore, the specific energy consumption (SEC) is given by:

$$SEC = \frac{\dot{W}}{Q_P} = \frac{\pi_0 R}{Y(1-Y)} \tag{3}$$

which is consistent with the SEC for a single-stage RO system (without recycling) that operates at the limit of the thermodynamic restriction [9]. This means that partial retentate recycling will not change the SEC of a single-stage RO desalting. The inclusion of an energy recovery device (ERD) will not alter this conclusion since the brine stream flow rate ($Q_B = Q_{raw} - Q_P$) and pressure (P_F), which determine the amount of energy that can be recovered [9], are the same for operation with and without partial retentate recycling.

2.2. Partial permeate recycling in single-stage desalting

For single-stage RO desalting with partial permeate recycling as shown in Fig. 1(b), the brine–permeate stream osmotic pressure difference is also given by $\Delta\pi_{\text{brine}} = \frac{\pi_0 R}{1-Y}$ assuming linear relationship between osmotic pressure and salt concentration [13]. When desalting at the limit of the thermodynamic restriction, the feed pressure is also as in Eq. (1). Given a recycled stream flow rate of $Q_{rec} = \alpha Q_P$, where α is the recycle-to-product ratio ($\alpha > 0$), the rate of pump work for a feed flow rate Q_F is given as

$$\dot{W} = \Delta P \times Q_F = \frac{\pi_0 R}{1-Y} \times (\alpha Q_P + Q_{raw}) \tag{4}$$

where

$$Q_F = Q_{rec} + Q_{raw} = \alpha Q_P + Q_{raw} \tag{5}$$

Therefore, the SEC for this system is given by

$$\begin{aligned} SEC &= \frac{\Delta P \times Q_F}{Q_P} = \frac{\pi_0 R}{1-Y} \times \frac{(\alpha Q_P + Q_{raw})}{Q_P} \\ &= \frac{\pi_0 R}{Y(1-Y)} + \frac{\alpha \pi_0 R}{1-Y} \end{aligned} \tag{6}$$

In Eq. (6), the first term, $\frac{\pi_0 R}{Y(1-Y)}$), is the SEC for a single-stage RO desalting at a water recovery of Y (Section 2.1, if one replaces the configuration inside the dashed region of Fig. 1(b) by a single-stage RO system without recycling). Thus, the SEC of single-stage RO desalting with partial permeate recycling is less energy favorable than single-stage RO desalting without partial permeate recycling. It is noted that if the pressure drop is taken into account, the SEC of partial permeate recycling operation will increase further. Likewise, the effect of an ERD will not change the above conclusion since the brine stream flow rate ($Q_B = Q_{raw} - Q_P$) and feed pressure (P_F) are the same for operation with and without partial permeate recycling [9].

The conclusion from the above simple analysis is that in a single-stage RO operation, permeate recycling increases the SEC, while retentate recycling does not change the SEC.

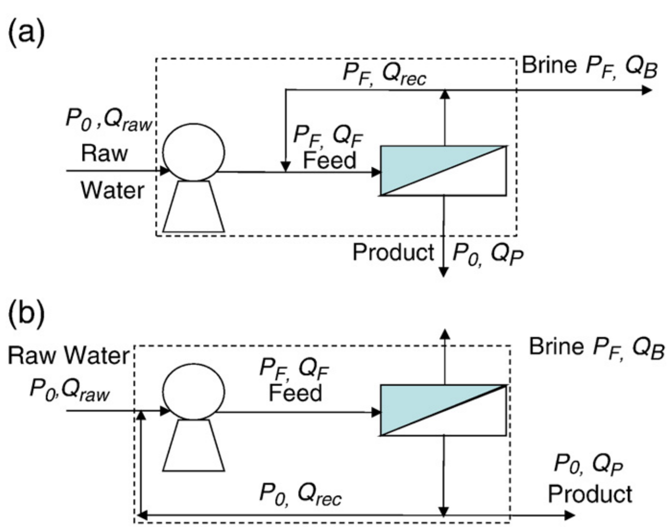

Fig. 1. Schematics of a single-stage RO system with partial retentate recycling (a) and permeate recycling (b).

3. Effect of second-pass retentate recycling to the first-pass feed in a two-pass membrane desalting process

A two-pass RO/NF desalting has been proposed in the literature as a potential approach to lower energy consumption [14] or to achieve target salt rejection which is not feasible with a single-pass [15]. Recent analysis has shown that the two-pass process without recycling has no