Batch reverse osmosis: a new research direction in water desalination

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Water scarcity is one of the grand challenges across the world [1]. Spiral wound reverse osmosis (RO) desalination is the most popular industrial technology to produce portable water from saline water resources. In terms of flow pattern, it falls into the category of cross-flow filtration where feed flows tangentially along the membrane surface while filtrate permeates across the membrane. One advantage of the cross-flow filtration over the dead-end filtration is that the filter cake does not build up substantially during operation, thus enabling continuous operation. The spiral wound configuration also maintains a good balance among packing density, ease of cleaning, water flux, and fabrication cost.

In continuous operation of industrial RO, 6–8 spiral wound elements are enclosed in a pressure vessel and multiple pressure vessels in parallel form a stage. Like all other cross-flow filtration processes, the salt concentration increases as the feed travels down the pressure vessel, resulting in a significant variation in driving force and water flux in seawater desalination [2]. The unbalanced flux (or high flux in lead elements and low flux in tail-end elements) is an inherent problem in cross-flow filtration, which imposes an adverse effect on energy efficiency. Because the energy required to drive pumps may reach up to 45% of the total cost in seawater RO, tremendous research and development efforts have been made in reducing the Specific Energy Consumption (SEC). One possible solution is to employ multistage design with interstage booster pumps, which enables a ramping-up pressure profile. Fig. 1a and b show the solutions to applied pressures, area allocations, and retentate flow profiles for \( \gamma = 2 \) for a 40% recovery using an optimization model [3]. Here \( \gamma \) is a dimensionless design parameter denoting membrane capacity demand ratio \( \gamma = A_m L_p \pi_0 / Q_o \), where \( A_m \) is membrane area, \( L_p \) membrane hydraulic permeability, \( \pi_0 \) feed osmotic pressure, and \( Q_o \) feed flow rate. In all configurations, the areas bounded by applied and osmotic pressures are the same \( \left( Y = m \int_0^{L_p} (P - \pi) dA / Q_o = \gamma \int_0^{L_p} (P / \pi_0 - \pi / \pi_0) d(A / A_m) \right) \). However, using more stages allows a more uniform driving force and water flux [3]. Note that the flux is proportional to the slope of \( Q \) in Fig. 1b. The advantage of multistage configuration is more evident when \( \gamma \) becomes larger, e.g., when membranes with a larger area or a higher permeability are adopted in plant design [3,4]. One obvious disadvantage is that as the number of stages increases, so does the number of interstage booster pumps. A spatially constant flux (i.e., a linear reduction of \( Q \) along the membrane) entails infinite number of RO stages if they are designed for steady-state operation, which is infeasible to implement. This raises an intriguing question: can dynamic operation achieve a uniform flux with the use of a limited number of pumps?

Recently, batch operation of RO has emerged as a potential energy-efficient desalination technique. The “Closed-Circuit Desalination” (CCD) is a concept of semi-batch RO (SBRO) proposed by Efraty in late 2000s [5]. Different from traditional steady-state RO, raw feed is sent to an RO unit at a time-varying pressure. The retentate is fully cycled, and the permeate rate is the same as the feed rate during the filtration step. Once a desired recovery is reached, a short flushing step is taken to replace the brine with a new batch of feed water, and the process repeats. Since then, research has been conducted by groups at Aston University [6,7], Yale University [8], Massachusetts Institute of Technology [9–12], University of California, Los Angeles [13,14] and California State Polytechnic University, Pomona [15] to advance the fundamental understanding and development of batch and semi-batch ROs. The difference between semi-batch and batch RO designs lies in the fact that the former involves undesirable mixing between the raw feed and solution already in the system. However, the latter usually requires varying-volume, high-pressure vessels, leading to complexity in design and operation.

Li [15] studied a batch seawater RO shown in Fig. 1c, which mimics a dead-end filtration using one cross-flow spiral wound element and a recycle stream. Li [15] clarified that retentate recycle in batch RO served to carry away salts rejected by the membrane. The recycle stream is unnecessary in batch RO if there exists a stirring mechanism within the RO element. This is different from retentate cycle in certain steady-state RO design, which often leads to an increase in SEC because of the elevated salinity in the feed [4]. Using optimal control theory, Li proved that the driving force and water flux should be constant throughout the entire filtration step in order to minimize SEC in batch RO. The optimal trajectories of the applied and osmotic pressures for \( Y = 50\% \) and \( \gamma = 1 \) are shown in Fig. 1d.

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A dimensionless parameter $\gamma = \frac{A_m t_p \pi_0 t_f}{V_0}$ (where $V_0$ is initial cylinder volume and $t_f$ is time duration), similar to the one used in steady-state RO, is proposed to characterize the energy performance [15]. The SEC normalized by $\pi_0$, or NSEC, in batch RO is [15]:

$$NSEC = \frac{\ln (1 - Y)}{Y} + \frac{J_w}{L_p \pi_0} = \frac{\ln (1 - Y)}{Y} + \frac{Y}{\gamma},$$  \hspace{1cm} (1)

where $J_w$ is water flux. At the thermodynamic limit (or $\gamma \to \infty$ or $J_w \to 0$ or driving force $\to 0$), the theoretical value of NSEC becomes $-\ln(1 - Y)/Y$. The advantage of using batch RO is evident when a large $\gamma$ or a large $Y$ is used in process design, similar to multistage design in continuous RO [15]. Li [15] further demonstrated that the energy efficiency of an ideal batch RO with temporally invariant flux is equivalent to that of continuous RO with infinite number of stages and booster pumps plus an ERD, where the flux is spatially constant.

In SBRO, the mixing of the fresh feed (of osmotic pressure $\pi_0$) and solution already in the cylinder (of osmotic pressure greater than $\pi_0$) results in undesirable entropy generation and inferior performance than batch RO. Let $Y$ be the water recovered per unit volume of the cylinder, the system recovery $Y = \frac{\tilde{Y}}{\tilde{Y} + 1}$. Consider a small time period when $\tilde{Y}$ changes to $\tilde{Y} + d\tilde{Y}$, the osmotic pressure in the cylinder is $\pi = \pi_0(\tilde{Y} + 1)$. Therefore, the theoretical NSEC at the thermodynamic limit is:

$$NSEC_{SBRO} = \frac{\int_0^Y \frac{\pi_0(\tilde{Y} + 1) d\tilde{Y}}{\pi_0 Y}}{\pi_0 Y} = 1 + \frac{1}{2} \tilde{Y} = 1 + \frac{Y}{2(1 - Y)}. \hspace{1cm} (2)$$

A comparison of batch RO and SBRO of seawater at the thermodynamic limit is shown in Fig. 1e. The benefit of batch designs is obvious at high recoveries. While industrial brackish water RO often has high recoveries, caution must be taken with the above conclusions, because its pressure drop effect is significant and it is usually operated far away from the thermodynamic limit, i.e., the transmembrane pressure is much greater in comparison to the transmembrane osmotic pressure [15].
(13% and 15% respectively) in comparison with the one in single-stage RO at a 50% recovery. Swaminathan et al. [11] also showed that batch designs with a pressurized feed tank and fewer membranes elements in series may reduce energy consumption by up to 8% in comparison with that of a continuous RO system. However, retrofitting a continuous seawater RO plant with an atmospheric feed tank to operate in the batch mode would not lead to energy savings, mainly because of energy cost associated with the cycle reset step.

Experimental studies have been carried out to explore salt retention during cycle reset. For example, Lee et al. [14] studied the brine flushing efficacy and its impact on SBRO during multiple cycles of filtration and flushing. The results indicated that the SEC in each cycle increased first and then stabilized with the progressive increase of cycle-to-cycle concentrate salinity caused by salt retention. Using longer flushing duration reduced the residual liquid and improved the performance of flushing process. Their analysis showed that the SEC of SBRO with complete flushing of brine was lower than that of the traditional steady-state RO without retentate recycle. However, ideal operations were difficult to reach. Experimental assessment of SBRO demonstrated a higher SEC against single-pass RO. Clearly, the performance of SBRO was significantly influenced by flushing efficacy of brine.

Several innovative prototypes of batch RO have been designed and tested. For example, Wei et al. [12] recently designed and established a “true” batch RO prototype with a flexible bladder. The terminology of “true” batch RO refers to a fully-pressurized design without the use of ERDs [12]. A model of batch RO energy consumption was developed and validated with measurement data. It was shown that the energy consumption was higher than the theoretical value due to incomplete flushing of brine, while it was lower than those in single- and multi-stage continuous RO. The predicted results with the proposed model indicated a 11% reduction in energy consumption for a seawater RO plant where feed salinity 35 g/kg, recovery 50%, and operating flux 15 LMH were specified. Davies et al. [6] proposed a piston-cylinder assembly that can be used to operate the batch RO without mixing the raw feed and solution already in the cylinder, thus overcoming the limitation of SBRO. Their theoretical analysis indicated that this “true” batch RO system consumed 33% less energy than SBRO at a recovery ratio of 80%. A prototype batch RO system was constructed and tested with various feed salinities (2,000–5,000 ppm) and recovery ratios (17.2%–70.6%). The results showed that the SEC of batch RO was better than that of single-stage continuous RO system with ERD. They further demonstrated a double-acting system that may compensate for the downtime in a batch RO [7].

In addition to SEC, fouling is another important issue in RO operation. Warsinger et al. [10] showed that batch RO had superior inorganic fouling resistance over conventional RO, which was attributed to its shorter residence time. The relatively uniform flux may also mitigate membrane fouling [12]. Lee et al. [13], however, demonstrated experimentally that SBRO was more prone to mineral scaling than steady state RO with partial recycle at the same overall recovery because of a higher nucleation rate. While an extended flushing in SBRO may mitigate scaling, a long filtration period with a high level of solution supersaturation is required to maintain the same recovery. Further investigations are required to reconcile these contradictory conclusions.

It is envisioned that batch RO will be a rapidly growing research area, which is driven by the need for innovative solutions to reduce SEC in seawater desalination. This research is complex in nature and necessitates a cross-discipline approach which brings together perspectives from membrane science, separation engineering and process systems engineering. Model-based systematic methods will continue to play an important role in conceptualizing process design and guiding experimental testings in order to further develop this promising energy-efficient desalination technique. Future research focuses may be toward developing novel “true” batch designs, enhancing flushing efficacy between filtration periods, and elucidating transient fouling and scaling mechanisms. For example, cyclic design ideas for batch RO may be brought from pressure swing adsorption (PSA), a mature industrial technology commonly used for gas separation. Advanced computing tools such as computational fluid dynamics (CFD) and optimal control may be used to explore and tailor spatial–temporal transport phenomena, for instance, dispersive mixing between the incoming feed and the outgoing brine during purging, salt retention during cycles, and their effects on fouling and SEC. Investigations may also be made on long-term durability of membranes during pressurization-depressurization cycles and techno-economic analysis of the batch designs.

Conflict of interest

The authors declare that they have no conflict of interest.

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