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Optimal seawater reverse osmosis network design considering product water boron specifications

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HIGHLIGHTS

- SWRO network design is presented with boron removal levels being considered.
- The performance of different RO element types were investigated using commercial membrane simulators.
- Boron rejection capacities for several membrane types were modeled using data from commercial simulators.
- pH adjustment calculations were enabled, as well as respective acid/base dosing requirements.
- Optimal designs were extracted using compact superstructure representations.

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ABSTRACT

This paper introduces a process synthesis strategy and optimization approach that accounts for boron removal considerations in Seawater Reverse Osmosis (SWRO) network design. The overall aim is to provide an improved understating of the performance of SWRO networks when specific requirements on boron levels in the system need to be met. In theory, this work utilizes the aspects of a well-defined SWRO network synthesis problem that has already been introduced in previous work, and builds on the existing representation by incorporating a number of fundamental aspects that facilitate boron removal in the system. This primarily included the determination of appropriate pH level conditions for the various network streams involved, in addition to the incorporation of a number of RO membrane element choices to be utilized in the system. Therefore, the design options allowed for the integration of a diverse mix of viable RO membrane elements within a single network, rather than strictly relying on one membrane type for all units. This was found necessary since different categories of RO membranes certainly have altered effects on the system's performance. Efforts directed towards investigating the effects of common operating parameters on boron rejection has been carried out by means of computer-aided membrane simulation tools, in which membrane performance in the form of boron rejection were converted to useful correlations that are then used in the optimization. A case study example involving three different seawater qualities, and correspondingly three different boron levels in each, was carried as a demonstration.

1. Introduction

Seawater reverse osmosis (SWRO) has emerged as the dominating technology to produce fresh water from seawater for many industrial and domestic applications [1]. The optimal configuration of membrane modules in such systems can be determined using network optimization approaches such as superstructure optimization [2–16]. The development of such approaches has focused on network representations that embed all possible configurations of processing units (membranes, pumps and ERDs) as well as efforts that account for full stream connectivity within the system. The representation of water quality in reverse osmosis network (RON) synthesis has received comparatively little attention despite its significance in design. Existing approaches typically consider only two lumped constituents to seawater, i.e. water and Total Dissolved Solids (TDS). In a first effort to address this limitation, we have recently introduced an approach to optimal RON synthesis that can track various constituents through the RON and enables the consideration of water quality parameters relevant in practice [17]. The removal options for boron, an important quality parameter for potable and agriculture irrigation water, cannot adequately be represented by the proposed approach due to its inability to enable pH adjustments in the network. This work aims at overcoming this limitation, and presents an extension to our previously developed approach that enables the extraction of optimal RON configurations whilst accounting for boron removal.

Average boron concentrations in conventional seawaters are at 4.5 mg/L [18–20]. However, boron levels may vary significantly,

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depending on the water source conditions. For instance, boron concentration levels in the Arabian Gulf and Mediterranean Seawaters can range from 7 up to 13 mg/L [18–20]. At pH conditions below 9, boron exists in the form of boric acid, a mononuclear poorly hydrated compound that is expected to penetrate a simple membrane barrier very easily. However, higher pH conditions increase the chance of forming borate ions as well as other poly-nuclear ionic compounds. This is attributed to further interaction between boric acid molecules and borate ions, which have more difficulty passing through the membrane [21].

$$B(OH)_3 + H_2O \rightleftarrows B(OH)_4^- + H^+$$

$$B(OH)_3 + 2B(OH)_4^- \rightleftarrows [B_3O_3(OH)_5]^{2-} + 3H_2O$$

Standard guidelines used for regulating boron concentration levels in water vary considerably between countries, depending on the expected water usage. For example, the WHO utilizes a limit of 0.5 mg/L (up from 0.3 mg/L) for boron content in drinking water, while the EU sets a standard of 1.0 mg/L as a threshold [22]. Many countries utilize provisional boron restrictions that are subject to further adjustment upon the evaluation of possible outcomes, especially since excessive boron consumption can prove to be very toxic to human beings in many situations [23]. Moreover, despite the progressive improvements in various commercial membrane materials, as well as in manufacturing procedures utilized, boron removal efficiencies using standard seawater RO membranes remain considerably lower than those for sodium chloride. For strict Boron limits in the product water, Boron can represent the performance limiting water quality parameter for SWRO process design. As a result, standard boron removal techniques, including efficient strategies for process design that achieve low boron levels in the permeate, are developed to enhance boron removal in seawater desalination [18–21,23–27]. In light of the above, it is important to capture boron removal options within the SWRO network synthesis problem. Sassi and Mujtaba recently introduced a Mixed Integer Nonlinear Programming optimization framework for evaluating boron rejection in RON networks, based on solution diffusion and thin film theory models. The developed RO network superstructure incorporates two seawater RO units, and one brackish water RO unit, each of which incorporating the corresponding types of RO membrane modules. Based on the proposed superstructure, RO network designs with desired limits on boron concentration within the permeate stream were attained [28].

This paper introduces an approach to RON synthesis that is capable of addressing boron removal, while building upon our previously introduced design representation that enables the extraction of optimal SWRO networks for alternative design classes [16] and presents an extension to our approach for optimal RON considering multiple water quality parameters in the system [17].

2. Standard boron removal options in SWRO networks

In order to effectively achieve acceptable boron concentration levels in the permeate according to WHO guidelines and other regularly recommended limits [21,23–25], many standard seawater desalination processes in practice use of a number of RO unit passes in the system. The first unit usually reduces the amount of total dissolved solids under high pressure conditions, thus allowing lower pressure RO membranes to be used in subsequent passes. It has been reported that it is sometimes very difficult to achieve the desired water recovery in the system, while still meeting severely strict boron guidelines under neutral pH conditions, even in designs that utilize RO membranes with enhanced boron removal capabilities (designed particularly for up to 95% boron rejection) [26]. It is important to note that the term 'boron rejection' refers to the selectivity a of particular membrane towards boron removal, and thus would be equivalent to the relative amount of boron that would pass onto the brine stream.

The number of passes to be used in a certain design usually depends on various aspects of the process such as the feedwater quality characteristics, as well as the desired product water specifications. As a matter of fact, incorporating unnecessary multi-passes in the system inevitably increase the operating cost [27,29]. It is also important to point out that operating individual passes under high pH conditions certainly enhances boron removal levels from the permeate stream. However, in order to avoid supersaturation of sparingly soluble salts under high pH conditions, appropriate antiscalant doses are to be maintained throughout, so as to prevent unwanted scaling phenomena [21].

2.1. Factors affecting boron rejection

In order to ensure accurate predictions that would allow introducing boron removal as an option in the design, a number of design variables influencing membrane boron rejection need to be taken into consideration simultaneously. These factors are discussed in the sections below.

2.2. Membrane type

The performance of an RON strongly depends on the type of membrane element chosen. It is therefore imperative to be able to appropriately select and use suitable RO membrane types in SWRO systems. Generally speaking, seawater RO membranes are often associated with higher boron rejection capacities, compared to brackish water RO membranes under various flux, pressure and temperature conditions [21,23].

2.3. pH

The solution pH significantly influences membrane boron rejection capacity. High pH solutions ($pH > 10$) induce the dissociation of boric acid BO_3 and the formation of negatively charged ionic borate $B(OH)_4^-$ which is larger in molecular size compared to the neutral boric acid form. As a result, electrostatic interactions between the negatively charged membrane surface and negatively charged species enhance boron removal. Many research efforts investigating the effect of the solution pH on boron rejection report similar trends [30–40]. It is therefore important to enable pH adjustments in RON synthesis to enhance Boron removal.

2.4. Operating temperature

The boron diffusion rate through RO membranes, or boron permeability, is dependent on operating temperature. The pKa value of boric acid and hence the speciation of boric acid in solution is also temperature dependent; however, the temperature effect on boron permeability is more pronounced. Hung et al. [26] and Hung and Kim [33] reported an inverse relation between temperature and boron rejection. Thus, an increased system temperature results in a reduced boron rejection capacity.

2.5. Operating pressure

Increasing operating pressure within the system causes an increase in water flux, as well as a higher concentration polarization modulus [21]. Moreover, the dilution effect of permeate water due to increased water flux, as a result of higher operating pressure causes an overall increase in boron rejection [25]. Therefore, employing maximum pressure conditions is recommended for attaining higher boron rejections.

2.6. Feed salinity

Feed salinity (ionic strength) is reported to have a certain influence on the boron rejection by RO membranes. This has been attributed to