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A systematic optimization of Internally Staged Design (ISD) for a full-scale reverse osmosis process

Kwanho Jeong[a], Minkyu Park[b], Seo Jin Ki[a], Joon Ha Kim[a,*]

[a] School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, South Korea
[b] Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

In this study, Internally Staged Design (ISD) was numerically optimized in order to demonstrate the long-term performance of full-scale seawater reverse osmosis (SWRO) membrane systems in the presence of colloidal foulants. To this end, a numerical model based on a finite difference method was developed and optimized with various feed water qualities, such as fouling potential and total dissolved solids (TDS). As a result, the optimized ISD exhibited greater water flux and higher energy efficiency in long-term operation (90 days) compared to conventional designs, where single-type membrane elements were employed over a pressure vessel while achieving potable TDS concentration in permeate (< 400 mg/L). This enhanced performance was attributed to the reduction of colloidal fouling on the lead elements and the alleviation of concentration polarization (CP) at the tail elements. Among fouling mechanisms, cake-enhanced concentration polarization (CECP) played a dominant role in flux decline at the lead elements, whereas CP was the chief flux decline mechanism at the tail elements. In addition, it was found that the employment of a low-permeability membrane at the lead element was important to maintain acceptable TDS in the permeate at either high TDS or high fouling potential of feed water.

1. Introduction

Global water scarcity is evident and requires more efficient water treatment technologies in order to secure water resources with potable water qualities [1]. The reverse osmosis (RO) membrane process has been widely used in numerous water treatment applications such as desalination and water reuse because RO membranes can effectively remove various classes of contaminants including inorganic salts and organic micropollutants, such as pharmaceuticals and personal care products (PPCPs) as well as endocrine-disrupting compounds (EDCs) [2]. In addition, its ease of operation and absence of byproduct formation make the RO membrane process a preferable option over oxidative water treatment processes such as advanced oxidation processes (AOPs), which include ozone oxidation, ultraviolet (UV) radiation, and so on. [3–5].

Despite the advantages of the RO process, there remain concerns about its high operation and maintenance (O & M) costs for driving high pressure and the cleaning/replacement of membranes [3]. A critical issue that jeopardizes the energy and cost efficiency of the RO process is membrane fouling. In particular, the accumulation of colloidal particles on a membrane surface forms a cake layer—one of the major fouling mechanisms in RO processes [6]. The colloidal fouling layer can further aggravate the permeate flux and solute rejection of a membrane by increasing not only hydraulic resistance but also the cake-enhanced concentration polarization (CECP) [7]. The CECP is a phenomenon in which the diffusive flux of salt ions away from the membrane surface are inevitably hindered within the deposit layer [7], thus augmenting osmotic pressure (i.e., cake-enhanced osmotic pressure, CEOP) [8]. Eventually, the reduced net driving pressure (NDP) due to the CEOP requires substantial energy consumption to achieve a designed flow rate.

In RO membrane filtration, the feed concentration gradually increases as the feed runs through the membrane elements; this is because the volume of water decreases due to its penetration through the membrane, while most of the salts are retained. The elevated salt concentration (therefore, the reduced NDP) at the tail elements causes much lower flux than at the lead elements, resulting in an uneven permeate flux distribution over a pressure vessel [9]. This flow imbalance is considerable in a conventional design that employs single-type elements in a vessel [10]. Such an element configuration also accelerates the uneven distribution of the cake layer formation. In colloidal fouling, for instance, the deposited foulant mass is proportional

* Corresponding author.
E-mail address: joonkim@gist.ac.kr (J.H. Kim).

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