Desalination 419 (2017) 60–69

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Effect of intermittent pressure-assisted forward osmosis (I-PAFO) on organic fouling

Jinwoo Lee[a], Seungho Kook[a], Chulmin Lee[a], In S. Kim[a,b,*]

[a] School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology (GIST), 123 Cheomdangwagi-ro, Buk-gu, Gwangju 61005, South Korea

[b] Global Desalination Research Center, Gwangju Institute of Science and Technology (GIST), 123 Cheomdanwagi-ro, Buk-gu, Gwangju 61005, South Korea

ARTICLE INFO

Keywords:
Intermittent pressure-assisted forward osmosis (I-PAFO)
Pressure assisted-forward osmosis (PAFO)
Organic fouling
Pressure relaxation
Physical cleaning
Fouling mitigation

ABSTRACT

This study investigated the feasibility of intermittent pressure-assisted forward osmosis (I-PAFO) operation for organic fouling mitigation, using sodium alginate as the model foulant. FO and PAFO were also operated to compare system performances in terms of water flux behavior, flux recovery by physical cleaning, fouling propensity, energy consumption, and membrane area required. Results showed that I-PAFO obtained higher water flux and flux recovery by physical cleaning than PAFO because of its lower fouling tendency. I-PAFO was able to reduce not only the accumulated foulant mass on the membrane surface, but also fouling layer compaction through the intermittent pressurization. Furthermore, it displayed benefits in terms of reducing membrane area required and operating energy compared to PAFO, due to its higher water productivity and sustainability. Therefore, I-PAFO can be a plausible option for saving membrane costs and operating energy when FO operations are concerned particularly in accordance with hybridization with RO (i.e. I-PAFO-RO hybrid process).

1. Introduction

Forward osmosis (FO) process utilizes the natural osmotic driving force for water transport across a membrane caused by the concentration difference between a low concentration of feed water and a high concentration of draw solution [1,2]. FO has been considered in recent decades as a good alternative for desalination and water treatment because of its potentially lower energy consumption and the fact that it has less membrane fouling compared to pressure-driven membrane processes such as reverse osmosis (RO) [3–5].

However, there have been limitations on the development of large-scale applications of FO, even though it has several benefits [6]. One of the major limitations is the concentration polarization phenomenon, which causes a reduced osmotic pressure driving force and thus results in a lower water flux than expected [2,5–8]; the reverse solute flux is also responsible for reductions in the osmotic driving force [7]. Furthermore, in terms of economic aspects the need for a post-treatment, i.e., the need for an additional energy-consuming process to recover the draw solute, is considered as another drawback of FO for use as a standalone process [5,7,9]. For these reasons, researchers have focuses their efforts on attempts to enhance the feasibility of FO process in ways such as applying FO to alternative hybrid processes such as FO-RO [7,9,10], membrane performance improvement [11], and pressure assisted-forward osmosis (PAFO).

PAFO has recently been suggested as a concept for improving the performance of FO. In PAFO, a hydraulic pressure is applied on the feed side, and as such the combined actions of osmotic and hydraulic pressures are used simultaneously as the driving force for water transport [7]. PAFO has the potential to resolve a key limitation of FO, which is its low permeate water flux. The additional hydraulic pressure enhances the permeate water flux over concentration polarization and reduces reverse salt diffusion [5–7,12,13]. Furthermore, PAFO can be applied in FO-RO hybrid processes as the PAFO-RO configuration, since the low water flux of FO is still regarded as economically inappropriate for FO-RO processes due to its high investment costs. In the FO-RO configuration, FO is used as pretreatment of RO, using secondary wastewater effluent and seawater as the feed water and draw solution, respectively, to dilute the seawater and thereby lead to energy savings in the RO process. The enhanced water flux of PAFO enables a greater dilution of seawater than FO, resulting in more energy savings in the RO step. PAFO also enables the use of a lower membrane surface area demand, further reducing membrane costs [10,14].

However, the action of hydraulic pressure in PAFO causes an increase in the membrane fouling severity, which is inevitable in

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[*] Corresponding author at: School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology (GIST), 123 Cheomdangwagi-ro, Buk-gu, Gwangju 61005, South Korea.

E-mail address: iskim@gist.ac.kr (I.S. Kim).

http://dx.doi.org/10.1016/j.desal.2017.06.003
Received 22 February 2017; Received in revised form 1 June 2017; Accepted 5 June 2017

Table 1
Experimental conditions.

Factors	Description	Note
Membrane	PA-TFC (CSM FO-8040, Toray Chemical Korea Inc., Korea)	Effective area 18.75 cm^2 (2.5 cm × 7.5 cm), Active layer facing feed solution (AL-FS)
Feed solution (FS)	2000 mg/L NaCl, 1 mM Ca^{2+}	2 L, pH 8.2 ± 0.2,
Draw solution (DS)	0.6 M NaCl	2 L
Model foulant	Sodium alginate (Sigma-Aldrich, USA)	250 mg/L in FS
Operation types	① FO ② PAFO ③ I-PAFO	
Applied pressure (bar)	0, 7.5	FO (0), PAFO (7.5), I-PAFO (0, 7.5)
Operation time	Until 500 mL of permeate volume is accumulated	15 min for physical cleaning
Flow rate	300 mL/min (CFV 6.667 cm/s)	700 mL/min (CFV 15.556 cm/s) for physical cleaning
Temperature	25 ± 1 °C	

pressure-driven membrane processes. A study observed that the fouling layer density increased (volume increased while thickness decreased) in the order of FO, PAFO, and RO as the proportion of hydraulic pressure out of the total driving force increased, thus indicating that a more compact and denser fouling layer is formed under higher hydraulic pressure whereas a looser and sparser fouling layer is formed under osmotic pressure as the major driving force [15]. Physical cleaning, i.e., the application of a high crossflow velocity to remove foulants, is also affected by the fouling layer structure. The more compact, denser fouling layer results in lower physical cleaning efficiency, whereas the looser and sparser fouling layer can be almost completely removed [15–19]. Because of the great amount of the foulants and fouling layer compaction, the fouling layer resistance for water transport increases, and the permeate water flux significantly drops [19]. The water flux decrease and low cleaning efficiency caused by membrane fouling in pressure-driven membrane processes deteriorates the overall process efficiency and shortens the membrane replacement cycle, negatively affecting water productivity and economical aspects [20]. Therefore, during PAFO operation, it is important to mitigate membrane fouling caused by the action of hydraulic pressure and to control fouling reversibility to effectively utilize the advantages of PAFO and its sustainable operation.

Pressure relaxation has been studied by many researchers as one of the physical methods to control membrane fouling such as air scouring and backwash [21,22]. Several studies verified the enhanced back transport of foulants from the membrane surface to the bulk solution due to the concentration gradient under pressure relaxation [23,24]. Another study directly observed biofilm compaction and relaxation (decompaction) caused by permeate flux variations, which causes a permeate drag force for fouling layer compaction, where the compacted biofilm returned to its initial state after restoring the original flux [25]. Intermittent operation, which repeatedly applying the pressure relaxation in a membrane bioreactor was able to maintain a higher water flux than continuous operation throughout the operation, with improved cleaning efficiency [23]. Intermittent operation applying pressure relaxation was also effective in increasing the average water flux in dead-end ultrafiltration, and more efficient flushing was achieved [26].

In PAFO research, there has been no comprehensive evaluation of intermittent operation on fouling mitigation performed, in spite of its proven effect with regards to pressure relaxation on the fouling layer in pressure-driven membrane processes. Continuous and discontinuous operations in PAFO were investigated, though the intent of the study was to evaluate the operation performance without foulants, focusing on the tendencies of water flux and reverse salt diffusion [5]. One study determined that the most efficient cleaning method was osmotic backwash [19], but there has been no study investigating fouling mitigation methods in the middle of operation.

Therefore, the objective of this study is to evaluate the feasibility of intermittent pressure-assisted forward osmosis (I-PAFO) operation to mitigate organic fouling by considering a PAFO-RO hybrid process concept. We operated FO, PAFO, and I-PAFO using solutions that includes sodium alginate as a model organic foulant, and assessed performances by comparing the water flux behavior, fouling propensity, physical cleaning efficiency, and energy consumption. Furthermore, consecutive batch tests were conducted in order to assess the feasibility of I-PAFO for potential use in long-term operation. The required membrane area was also calculated, based on assumptions obtained from the results of consecutive batch tests.

2. Materials and methods

2.1. FO membrane

Thin film composite (TFC) FO membrane coupons were used for the experiments, which were cut from an FO spiral wound membrane module (CSM FO-8040, Toray Chemical Korea Inc., Korea). The TFC membrane has an asymmetric structure that consists of a selective polyamide active layer formed by interfacial polymerization on the top of a polysulfone porous substrate [10,27]. Prior to use, the membrane coupons were soaked in deionized (DI) water and stored at 4 °C. More details of the experimental conditions of the FO membranes are given in Table 1 in Section 2.4.

2.2. Organic foulant and solutions preparation

Sodium alginate (Sigma-Aldrich, USA) was used as the model organic foulant. Sodium alginate is considered as a foulant that represents polysaccharides, as it constitutes a major portion of soluble microbial products (SMPs) in secondary wastewater effluent. The molecular weight of alginate ranges from 12 to 80 kDa [28]. The alginate was purchased in powder form. Prior to making the feed solution (FS), 5 g/L of an alginate stock solution was prepared by dissolving the powder in DI water. The solution was stirred for 24 h to ensure that the alginate was completely dissolved. Next, the solution was stored at 4 °C. Overall, 2 L of FS was made, including 2000 mg/L of NaCl and 1 mM Ca^{2+}, and 250 mg/L of alginate was added from the stock solution. The FS solution pH adjusted to 8.2 ± 0.2 using 1 M NaOH solution; 2 L of a 0.6 M NaCl solution (OCI Company Ltd., Korea) was used as the draw solution (DS) (Table 1).

2.3. I-PAFO system

A schematic diagram of the I-PAFO system is given in Fig. 1. In brief, a bench-scale osmosis-driven crossflow system was used to perform FO, PAFO, and I-PAFO. An acrylic FO cell consisting of two rectangular channels (dimensions: 7.5 cm (L) × 2.5 cm (W) × 0.3 cm (D)) on either side of the cell in order to circulate the FS and DS. The DS channel was filled with eleven permeate carriers which were cut from the FO spiral wound module (CSM FO-8040, Toray Chemical Korea Inc., Korea) to prevent the FO membrane being damaged by the hydraulic pressure applied from the FS side, whereas FO channel did not have a feed spacer. A Magnetic drive gear pump (GAF-T23-DEMSE,