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Understanding the possible underlying mechanisms for low fouling tendency of the forward osmosis and pressure assisted osmosis processes

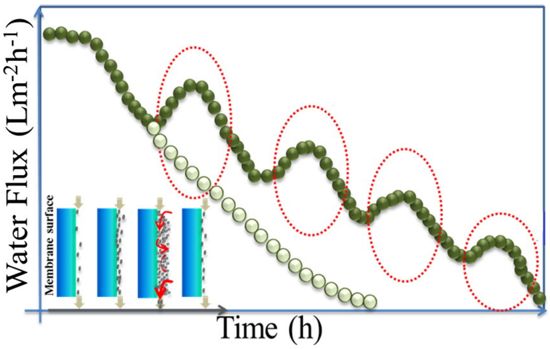
Fezeh Lotfi [a,1], Laura Chekli [a,1], Sherub Phuntsho [a], Seungkwan Hong [b], Joon Young Choi [c], Ho Kyong Shon [a,*]

[a] *School of Civil and Environmental Engineering, University of Technology Sydney (UTS), City Campus, Broadway, NSW 2007, Australia*
[b] *School of Civil, Environmental & Architectural Engineering, Korea University, 1, 5-ka, Anam-Dong, Sungbuk-Gu, Seoul 136-713, Republic of Korea*
[c] *Hyorim Industries Inc., Yatap-dong, Bundang-gu, Seongnam City, 513-2, Gyeonggi-do, Republic of Korea*

HIGHLIGHTS

- An interesting water flux pattern was observed during osmotic dilution of seawater.
- It was related to the build-up of loose fouling layer peeled-off from the surface.
- This sinusoidal flux pattern was highly dependent on the operating parameters.
- Intrinsic membrane cleaning strategies can be adopted; avoiding plant down time.
- Increasing the feed cross-flow velocity at specific time was found most efficient.

GRAPHICAL ABSTRACT



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ABSTRACT

We investigated the possible underlying mechanism of the low fouling potential in the forward osmosis (FO) process during the osmotic dilution of seawater as part of the simultaneous desalination and wastewater reuse by FO and reverse osmosis hybrid system. Long-term experiments revealed an interesting water flux pattern highly dependent on the different operating parameters. The most interesting observation made was the spontaneous increase in the FO permeate flux at regular time interval during the FO operation using synthetic wastewater as feed and seawater. This sinusoidal FO flux pattern related well with the build-up of loose fouling layer and their natural peel-off from the membrane surface upon reaching certain layer thickness due to crossflow velocity shear. This flux pattern was more prominent at higher cross-flow velocity rates, lower feed water pH, for a smoother membrane surface and at lower operating pressure during pressure assisted osmosis (PAO) mode. Based on these results, membrane cleaning strategies were proposed by targeting a higher cross-flow velocity shear at a time when the permeate flux started to just increase. The approach of physical membrane cleaning was observed efficient and was able to almost fully restore the initial flux even under the PAO operation at 4 bar.

1. Introduction

The sustainability of water and energy resources is being threatened due to rapid population growth and therefore, developing low-energy separation technologies is crucial to meet the increasing water demand

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[*] Corresponding author.
E-mail address: hokyong.shon-1@uts.edu.au (H.K. Shon).
[1] F.L and L.C. equally contributed to this work.

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through unconventional sources [1–4]. Membrane technologies are currently the most widely applied techniques to produce clean water and reverse osmosis (RO) is the most employed membrane process for desalination (up to 70% of the installed desalination plants) [5]. Although the RO desalination plants consume significantly less energy than it was decades ago due to the efficient energy recovery devices and improved membrane materials, desalination still remains an energy-intensive process [6,7]. Besides, the energy required for RO desalination has almost reached its thermodynamic limit and the remaining opportunities to further reduce its energy consumption will require additional processes which ultimately increase the total cost of the final water [8]. Moreover, RO still suffers from severe membrane fouling; affecting its long-term performance and the cleaning of membranes not only has considerable environmental issue but also pose a significant plant downtime. Therefore, any novel low-cost desalination technology that could circumvent those issues will have significant impact in sustaining the water and energy sources.

Recently, forward osmosis (FO) has received increased interest as an emerging low-cost desalination technology. The term low-cost has been often attributed to this process since it relies on a natural driving force (i.e. the osmotic pressure difference across the membrane) that draws the water from a saline feed water (e.g. seawater) to a highly saline draw solution (DS). Apart from its apparent low-energy requirements, FO process also showed much lower fouling potential compared to other conventional pressure-driven membrane processes such as RO [9,10]. Fouling has been found to be physically reversible in most cases, reducing the need for chemical cleaning [11,12]. However, one of the main barriers that impede the commercialization of this process is the separation of the produced water from the draw solution [13–15]. In fact, the success of FO for clean water production is greatly dependent on how efficient (i.e. performance and cost) the DS separation and recovery process is [16].

In the last decade, several hybrid FO systems (i.e. FO coupled with another process) have been developed for various applications, including mainly seawater and brackish water desalination, wastewater treatment and both (i.e. simultaneously) [17]. For the latest, the hybrid FO-RO system has attracted increased attention since FO can be used as an advanced desalination pretreatment process to dilute the seawater and therefore moderate the energy requirement during RO desalination [18–21]. Besides, the low salinity of most wastewaters makes them suitable candidates for this osmotic dilution [22]. The main advantage of this hybrid process is that the FO process operates in the osmotic dilution mode (i.e. both the concentrated feed and diluted draw solutions are the target) which eliminates the energy associated with the DS recovery process [23]. This hybrid process can be further extended if, after the RO process, the second FO process is used to further concentrate the wastewater which can be then used for agriculture applications (e.g. nutrient recovery) and, at the same time, dilute the RO brine for sustainable discharge.

In the present study, we investigated the long-term operation of the FO process during the osmotic dilution of the seawater using wastewater. This study focused on evaluating and understanding the fouling behaviour in the FO process for this specific application. The effect of different operating parameters (e.g. cross flow rate, feed water pH, applied pressure) on the fouling tendency has also been investigated. Finally, some fouling mitigation strategies have also been suggested to optimise the long-term FO operations.

2. Materials and methods

2.1. Feed and draw solutions

This study was carried out using synthetic seawater (SSW) as DS prepared by mixing 0.6 M sodium chloride (NaCl) solution in DI water (electrical conductivity or EC of 55.1 mS/cm, TDS 35 g/L and pH 6.5). Synthetic wastewater (SWW) was used as feed solution (FS) and its composition is summarised in Table 1. This SWW simulates effluent organic matter generally found in the biologically treated sewage effluent (BTSE) [24]. Tannic acid, sodium lignin sulfonate, sodium lauryl sulfate and arabic acid represent the larger molecular weight (MW) molecules while peptone, beef extract and humic acid consist of smaller MW compounds. Dissolved organic carbon (DOC) was measured using the Dohrmann Phoenix 8000 UV-persulfate TOC analyser equipped with an autosampler. All samples were filtered through 0.45 μm membrane prior to DOC measurements.

2.2. Forward osmosis membrane

A commercial flat-sheet cellulose triacetate (CTA) FO membrane (Hydration Technology Innovations or HTI, Albany, USA) was used in this study. The CTA membrane is made from cellulose acetate embedded in a polyester woven mesh, and the characteristics of this membrane are presented in Table 2. More information on the properties and characteristics of the CTA FO membrane can be found in other publications [25–27].

A commercial polyamide (PA) based thin film composite (TFC) FO membrane (Toray Industry Inc., Korea) was also used in this study to compare its performance with the CTA membrane. The pure water permeability coefficient of the active layer (A) was determined following a previous experimental protocol [28]. Briefly, the A value was measured at different operating pressures and was calculated by dividing the pure water permeate flux by the applied hydraulic pressure. The salt rejection (using 1.2 g/L Red Sea salt as feed) was also determined from the difference between the feed and permeate salt concentrations. The intrinsic properties of this membrane were found as follow: $A = 8.9 \pm 0.14\ \mathrm{L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}}$ and salt rejection of 85% (1.2 g/L Red Sea salt).

2.3. Bench-scale FO system and spacer design for pressure-assisted osmosis experiments

The performance and fouling tests of the FO process were conducted using a lab-scale FO membrane unit consisting of an acrylic FO cell with internal dimensions of 7.7 cm length, 2.6 cm width, and 0.3 cm depth (effective membrane area of $2.0.10^{-3}\ \mathrm{m^2}$). The schematic layout of the FO-RO hybrid process is presented in Fig. 1a, and similar to the unit used in our previous study [29]. Both the FS and DS were supplied at cross-flow velocities of 8.5 cm/s (i.e. 400 mL/min or Reynolds number (*Re*): 455), unless otherwise stated, under counter-current flow and in FO mode (i.e. active layer facing the FS). The temperature of the FS and DS was maintained at 25 °C using an automated heater/chiller control system connected to a water bath. All FO experiments were conducted in the batch mode of operation. The DS and FS were recycled back to their respective tanks after passing through the FO membrane cell thereby making process a batch operation. The initial volumes of both DS and FS were fixed at 2.0 L each. Before each experiment, the FO membrane was stabilised for 30 min using DI water on both sides

Table 1
Composition of the synthetic wastewater used in this study.

Compounds	Concentration (mg/L)
Beef extract	1.8
Peptone	2.7
Humic acid	4.2
Tannic acid	4.2
Sodium lignin sulfonate	2.4
Sodium lauryl sulfate	0.94
Arabic gum powder	4.7
Arabic acid (polysaccharide)	5
$(NH_4)_2SO_4$	7.1
K_2HPO_4	7
NH_4HCO_3	19.8
$MgSO_4 \cdot 7H_2O$	0.71

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