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Using modelling approach to validate a bench scale forward osmosis pre-treatment process for desalination

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HIGHLIGHTS

- Evaluation a batch laboratory-scale FO system as a pre-treatment for the RO process
- FO can help to avoid RO fouling and achieving higher overall water recovery
- Modelling takes into account flux, water recovery and the final draw concentration
- An experimental design methodology has been successfully applied for FO optimisation
- The optimal FO conditions are determined and validated by real brackish water

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ABSTRACT

Forward osmosis (FO) has recently attracted growing attention in wastewater, brackish groundwater and seawater desalination, and power generation. This study evaluates the potential of using a batch laboratory-scale FO system as a pre-treatment for the reverse osmosis (RO) process. FO is a low pressure-driven process that offers many advantages compared to the conventional pre-treatment for RO especially for brackish water with high potential of scaling and fouling. FO can help to reduce the RO process cost by avoiding RO membrane fouling and achieving higher water recovery. An experimental modelling has been employed to describe the FO process taking into account water flux, water recovery and final draw solution. Based on this experimental modelling, the energy consumption for RO has been estimated. It has been found that the treatment time for the FO process and the initial draw solute concentration are important parameters that have an interrelated effect on FO and RO efficiency. The optimal conditions for this FO pre-treatment process are determined by modelling and are experimentally validated by using real brackish water as feed in a bench-scale FO system.

1. Introduction

Over the last decades, as the demand for fresh water has increased and the available resources have decreased, desalination has become one of the most promising methods of producing drinking water. Where sufficient water cannot be provided using conventional resources or by recycling, the desalination of seawater or brackish groundwater offers an alternative solution [1].

Water desalination has been practised since the 1950s but a wider application at that time has been limited by technology, high capital costs and high energy consumption leading to high unit cost compared to conventional processes for freshwater production. Now, many improvements in reverse osmosis (RO) membrane development and recovery of energy from brine depressurisation means that the capital cost and energy consumption of the RO process have been significantly reduced, making it a feasible alternative method for freshwater production [2,3]. Among the different desalination technologies, RO represents the most economically and commercially significant technology for seawater and brackish water desalination [4].

Nevertheless, three key obstacles remain in RO technologies: high energy consumption, low water recovery and membrane fouling [5]. Most of the energy consumption in the RO process is related to the application of hydraulic pressure to overcome the osmotic pressure of sea or brackish water. Typically, energy consumption represents 44% of the total water cost of an RO plant [6]. The water recovery of a single-stage RO desalination system ranges from 40 to 60%. Low water recovery produces a large volume of concentrated brine, which needs to be disposed of and causes environmental concerns, especially for inland desalination plants where brine-discharging outlets are unavailable [7]. Finally, RO membranes are highly sensitive to organic, inorganic (scalant) and biofouling. Membrane fouling reduces the RO process efficiency (water recovery), reduces the life span of the membranes and increases the energy cost of the system. An efficient pre-treatment process is needed

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Nomenclature

ANOVA	analysis of variance
CCD	central composite design
CTA	cellulose triacetate
DI	deionised
ECP	external concentration polarisation
FD	factorial design
FO	forward osmosis
HU	Hazen units
NTU	nephelometric turbidity unit
ICP	internal concentration polarisation
PRO	pressure-retarded osmosis
RO	reverse osmosis
RSM	response surface methodology
TDS	total dissolved solids
TFC	thin-film composite
TOC	total organic carbon

to keep membranes in good condition and to maintain them for a reasonable period [8].

For treating the feedwater that contains high level of scaling ions, a new membrane process called forward osmosis (FO) appears to be one of the most promising pre-treatments for protecting RO membrane from scaling and fouling by this "difficult" water. FO is an osmotically driven membrane process that takes advantage of the osmotic pressure gradient to drive water across the semipermeable membrane from the feed-solution (low osmotic pressure) side to the draw-solution (high osmotic pressure) side [9–11]. As a result of the very low hydraulic pressure required, FO provides many potential advantages over pressure-driven processes like RO, such as less energy input [12], lower fouling tendency, easier fouling removal [13–15] and higher water recovery [16,17]. The objective of using FO as a pre-treatment is to remove bacteria and viruses as well as organic and inorganic compounds such as polysaccharides, proteins and scaling ions by filtration, as these compounds are largely responsible for RO membrane fouling and scaling. Following the FO process, the solution contains only mostly single species of salt (draw solute) in fresh water, which has low scaling and fouling potential for the RO membrane. Recently, the combination of FO and RO has been used in some laboratory-scale experimental study and in limited industrial applications [18–22] but no systematic analysis has been conducted to optimise the operational parameters. FO pre-treatment offers many advantages compared to other pre-treatment but generally results to higher salinity solution that required RO process, and leading to higher energy cost. As a result, FO seems to be a suitable pre-treatment for desalinating water with high fouling and/or scaling potential such as brackish ground water [20].

The objective of this study is to develop a modelling approach that can describe the FO process when it is used as a pre-treatment for brackish water desalination. An experimental design methodology has been used for evaluating the FO process in terms of water flux, water recovery and final draw solution concentration. Considering the integrated FO–RO system, the draw solution, which is diluted by extracted water from the feed (FO process), will be regenerated by using RO process. In a perspective of optimisation, the RO energy consumption has been estimated (by models) using the experimental FO results. Theses developed models are used to optimise water flux and water recovery of FO process and energy consumption of RO process. The optimal operational parameters predicted by the model are validated by the experimental results and the best conditions are applied to real brackish water.

2. Materials and methods

2.1. Feed and draw solutions

The synthetic feed solution was prepared by dissolving the appropriate quantities of sodium chloride (NaCl) in 1.5 l of deionised water and stirring the mixture for at least 20 min. Two types of salt (NaCl and Na_2SO_4) were used to prepare the draw solutions. The appropriate amount of salt was added to 1.5 l of deionised water to obtain a salt concentration varying from 0.66 M to 2.34 M. Sodium chloride and anhydrous sodium sulphate were obtained from Rowe Scientific, Australia.

Once the optimal operational conditions for this FO process were determined, real brackish groundwater was used as feed to validate these conditions. The feed–water samples were obtained from a groundwater bore at Mawson Lakes (Mawson Lakes, South Australia) and contains of $1.77 \pm 0.03\ g \cdot L^{-1}$ TDS (total dissolved solids), $0.5 \pm 0.3\ mg \cdot L^{-1}$ TOC (total organic carbon), $86.5 \pm 0.1\ mg \cdot L^{-1}$ calcium and $56.2 \pm 0.05\ mg \cdot L^{-1}$ magnesium. The pH of this groundwater was 7.90 ± 0.25, with a colour and a turbidity of <1 HU and 5.4 NTU respectively. Samples were collected and stored in polypropylene containers at 4 °C until use. Before each experiment, the temperature of the samples was adjusted to 22 °C and the concentration of TDS was increased to $10\ g \cdot L^{-1}$ by adding NaCl.

2.2. Bench-scale FO experiments

The experiments were conducted in batch mode using a bench-scale FO membrane system as depicted in Fig. 1. The FO system consisted of a flat-sheet membrane contact cell with two identical compartments separated by a FO membrane, two peristaltic pumps, flow metres and two containers: one for the feed and the other for the draw solution. Flat-sheet cellulose triacetate (CTA) and thin-film composite (TFC) FO membranes (Hydration Technology Innovations, Albany, Oregon, USA) were used in this study.

The circular membrane contact cell has symmetric channels on both sides of the membrane. The FO cell has spiral baffles creating channels with 3.2 cm width. The active surface area of each cell is 105 cm^2. Plastic mesh spacers were used in both channels to support the membrane and also to increase turbulence and reduce external concentration polarisation (ECP) on both sides of the membrane. Depending on the mode of filtration, the orientation of the membrane is different. In FO mode, the active layer of the membrane is oriented towards the feed-solution channel, while in PRO mode, the active layer is oriented towards the draw solution.

The feed-solution container was placed on a balance (MS 1600l, Mettler-Toledo, Switzerland) to determine water flux by measuring the variation in the weight of the feed solution according to Eq. (1):

$$J_w = \frac{\Delta \text{weight}}{\text{water density} \times \text{effective area} \times \Delta \text{time}}. \quad (1)$$

Water recovery was used to determine the concentration increase of the feed water and was calculated using Eq. (2):

$$\text{Water recovery}(\%) = \frac{V_{permeate}}{V_{feed}} \times 100 \quad (2)$$

where $V_{permeate}$ and V_{feed} are the permeate and initial feed volumes respectively.

The reverse salt diffusion has been determined by measuring the concentration of the solute in the feed solution (pure DI water). The concentration of salt in solution has been calculated by conversion of the conductivity of the solution.