Desalination 377 (2016) 138–151

Contents lists available at ScienceDirect

Desalination

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

Energy consumption for desalination — A comparison of forward osmosis with reverse osmosis, and the potential for perfect membranes

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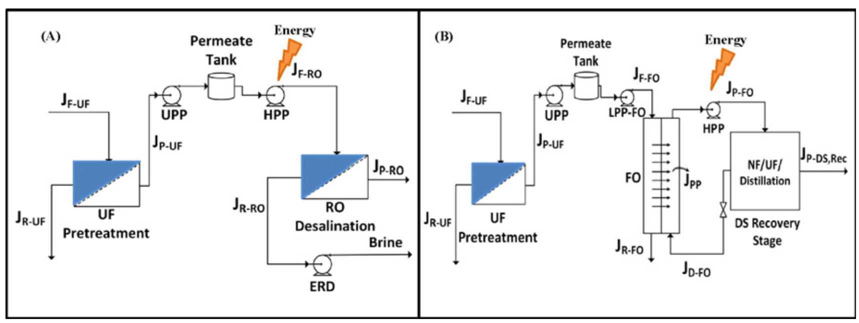
HIGHLIGHTS

- Custom AspenONE models are developed for quantifying SEC of RO and FO desalination.
- There is no difference in SEC between RO and FO with nanofiltration DS recovery.
- RO competitive with FO despite pressure-driven membrane process for DS recovery
- Infinite membrane permeability does not reduce SEC significantly.
- Advantage of FO derives from lower fouling propensity and specific applications.

GRAPHICAL ABSTRACT

Desalination process flowsheets considered in this study for comparison of SEC.
(A): RO desalination process with UF membrane pretreatment.
(B): FO desalination process with UF membrane pretreatment and varying draw solution recovery methods.



ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 14 August 2015
Accepted 17 August 2015
Available online 24 September 2015

Keywords:
Desalination
Energy consumption
Forward osmosis
Reverse osmosis
Membrane processes

ABSTRACT

Reverse osmosis (RO) is now the most ubiquitous technology for desalination, with numerous seawater RO plants being built in water-stressed countries to complement existing water resources. Despite the development of highly permeable RO membranes, energy consumption remains a major contributor to total cost. Forward osmosis (FO) is receiving much attention as a potentially lower energy alternative to RO. However, the draw solution (DS) recovery step in FO requires significant energy consumption. The present study is a modelling approach, simulating FO and RO desalination under various process conditions and process flow schemes using the Aspen Plus environment. Results suggest that there is practically no difference in specific energy consumption (SEC) between standalone RO, and FO with nanofiltration (NF) DS recovery; this can be generalised for any pressure-driven membrane process used for the DS recovery stage in a hybrid FO process. Furthermore, even if any or all of the membranes considered, FO, RO or NF, were perfect (i.e. had infinite permeance and 100% rejection), it would not change the SEC significantly. Hence, any advantage possessed by the FO with NF recovery process derives from the lower fouling propensity of FO, which may reduce or eliminate the need for pretreatment and chemical cleaning.

1. Introduction

Desalination is an attractive technology for the provision of clean water, due to the abundance of seawater. However, it is an energy intensive process compared to other water treatment technologies and poses

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http://dx.doi.org/10.1016/j.desal.2015.08.011
0011-9164/© 2015 Published by Elsevier B.V.

an environmental challenge in terms of brine discharge. Since the 1970s, seawater reverse osmosis (SWRO) has been the leading technology for seawater desalination, and over this period there has been a large improvement in SWRO energy consumption, from as much as 20 kWh·m^{-3} in the 1970s to nearly 2 kWh·m^{-3} at 50% recovery, now [1]. The practical minimum energy for desalination of seawater at 50% recovery is 1.56 kWh·m^{-3} [1], which suggests potential for further improvement. Recently, forward osmosis (FO) has been receiving increasing interest from academia and industry as a potentially lower energy alternative to SWRO. Given that energy consumption makes up a major portion of the SWRO cost, reaching as high as ~45% of the total permeate production cost [2], it is useful to take a step back and compare the practical energy needs for RO and FO, where FO employs various draw solution recovery methods.

There have been recent publications comparing the energy consumption of a standalone RO process with FO–RO hybrid process for desalination [3,4]. However these studies presented a thermodynamic comparison assuming idealised conditions, and without considering process details such as pressure drop and pretreatment. In this present study, we carry out a more detailed comparison taking the process factors into account. Furthermore, previous comparisons were limited mainly to the FO–RO hybrid process which our study has extended to include other potential draw solution recovery processes. We also carry out a detailed analysis on the potential improvements in membrane permeance on the specific energy consumed and specific membrane area requirements for the various systems, another factor not considered in previous studies.

Published research on SWRO has investigated reducing the SEC by optimising the membrane module [2,5–13] and/or using more permeable membranes [8,14–16]. However, these studies have utilised modelling tools [1,2] without process simulation tools. Most often pre-treatment energy requirements and pressure losses (if included at all in these previous studies) were adopted from other publications or plant data, rather than being quantified by the studies themselves [1,17–19]. Therefore, endogenous calculations on the effects of pretreatment and pressure losses in SWRO are in high demand.

For FO, the main direction of current research is towards improving intrinsic and transport properties of membranes on a molecular level [20–28]. However, the effects of these improvements on the energy efficiency of different FO desalination processes remain unexplored. Consequently, literature lacks comparative data on the SEC of different FO draw solution recovery processes, and how these compare with RO.

To reduce the sources of "side" factors which might compromise the comparison between RO and FO desalination, this present work utilises a unified process simulation environment, providing consistent numerical tolerances and sets of thermodynamic and physical properties models (in particular those embedded in the so called "Electrolytes NRTL" Property Method, available in Aspen's physical properties system) for all simulations. The mathematical models for all custom (non-library) unit operations were programmed in Matlab R2012b, and embedded in the Aspen Plus V7.3 environment. The interoperability between the modelling tool, Matlab, and the process simulation suite, Aspen One, was achieved using CAPE-OPEN interface standards, according to the methodology proposed in [29]. To the best knowledge of the authors, this is the first study which utilises Aspen Plus for simulation of FO and RO desalination processes using custom Matlab models. This customised process simulation approach allows for consistent evaluation and comparison of the energy requirements of FO and RO desalination along with the pretreatment stages, taking into consideration the effects of process configuration, the thermodynamic restriction, product water recovery, draw solution recovery, membrane permeance, applied pressure, draw solution concentration, external and internal mass transfer coefficients, pressure drop and the use of energy recovery devices.

Accordingly, the objectives of the present study are:

i) To quantify and compare SEC for desalination by RO and FO, considering for RO a range of process flow diagrams which account for the effects of pretreatment stages and pressure loss in the membrane modules, and for FO various draw solution recovery options;
ii) To evaluate the potential for improvements in membrane permeance and rejection to reduce the SEC for both RO and FO.

2. Process modelling and simulation

2.1. Process flow diagrams and unit operations

Fig. 1(A) and (B) show the two types of desalination processes that were investigated in this study:

A) Reverse osmosis (RO) with ultrafiltration (UF) pretreatment;
B) Forward osmosis (FO) with UF pretreatment and varying draw solution (DS) recovery methods, namely (a) NF for the recovery of $MgSO_4$ draw solution; (b) UF for the recovery of polyacrylic acid-nanoparticles (PAA-NP) and; (c) distillation for the recovery of CO_2–NH_3 draw solution.

In this study, the energy consumption of SWRO is simulated at various recoveries. Results obtained are compared with simulation of FO to assess if FO has the potential for energy savings compared to RO. A fixed total pure water flowrate of 666 m^3·h^{-1} (16,000 m^3·d^{-1}), emulating a medium sized desalination plant is used as a basis for calculation. A higher product recovery ratio reduces the total volume of feed water to be pretreated (and hence the cost of pretreatment), whilst maintaining the permeate flowrate. At higher recoveries, less seawater is discharged in the retentate and more is collected as the product water [30].

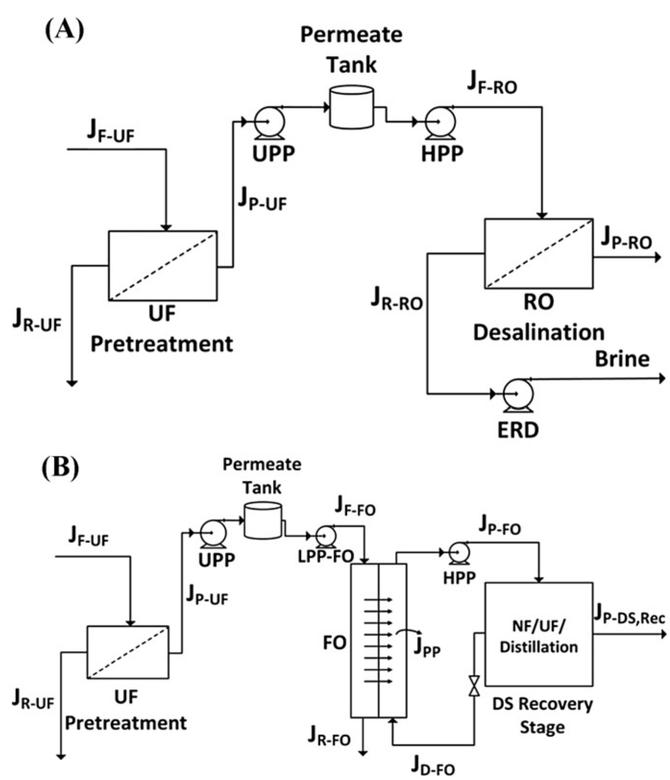

Fig. 1. Desalination process flowsheets considered in this study for comparison of SEC. (A): RO desalination process with UF membrane pretreatment. (B): FO desalination process with UF membrane pretreatment and various draw solution (DS) recovery methods.