Desalination xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Desalination

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

A closed-loop forward osmosis-nanofiltration hybrid system: Understanding process implications through full-scale simulation

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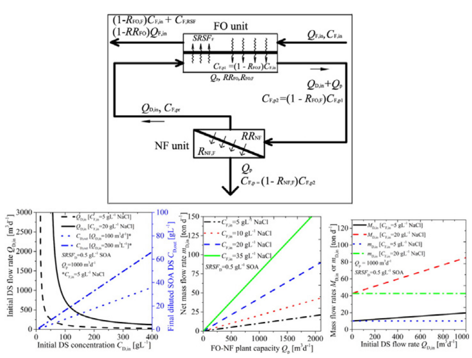
HIGHLIGHTS

- Initial DS flow rate and concentration cannot be set at any arbitrary values.
- Initial DS flow rate and concentration vary inversely for a fixed plant capacity.
- Net DS mass flow rate m_D is the most important parameter for a closed system.
- m_D is constant for a fixed plant capacity but increases with capacity and feed TDS.
- FO and NF rejection rates influence feed solute accumulation in the closed system.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 August 2016
Received in revised form 9 December 2016
Accepted 14 December 2016
Available online xxxx

Keywords:
Forward osmosis
Nanofiltration
Fertigation
Simulation
Desalination

ABSTRACT

This study presents simulation of a closed-loop forward osmosis (FO)-nanofiltration (NF) hybrid system using fertiliser draw solution (DS) based on thermodynamic mass balance in a full-scale system neglecting the non-idealities such as finite membrane area that may exist in a real process. The simulation shows that the DS input parameters such as initial concentrations and its flow rates cannot be arbitrarily selected for a plant with defined volume output. For a fixed FO-NF plant capacity and feed concentration, the required initial DS flow rate varies inversely with the initial DS concentration or vice-versa. The net DS mass flow rate, a parameter constant for a fixed plant capacity but that increases linearly with the plant capacity and feed concentration, is the most important operational parameter of a closed-loop system. Increasing either of them or both increases the mass flow rate to the system directly affecting the final concentration of the diluted DS with direct energy implications to the NF process. Besides, the initial DS concentration and flow rates are also limited by the optimum recovery rates at which NF process can be operated which otherwise also have direct implications to the NF energy. This simulation also presents quantitative analysis of the reverse diffusion of fertiliser nutrients towards feed brine and the gradual accumulation of feed solutes within the closed system.

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http://dx.doi.org/10.1016/j.desal.2016.12.010
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1. Introduction

Desalination is one of the most reliable solutions to fresh water scarcity problems, however, the existing desalination technologies are still highly capital and energy intensive processes [1,2] making desalination not cost-effective in general for irrigation. Recent efforts have been made to develop less capital and energy intensive desalination technologies such as forward osmosis (FO), applied to a wide range of applications. Unlike conventional desalination based on the reverse osmosis (RO) process, the FO process uses a natural osmotic driving force created by the concentration difference between the highly concentrated draw solution (DS) and the feed solution (FS) when separated by a semipermeable membrane. The concentrated DS is diluted during operation, enabling it to be used either directly if suitable or processed further to separate pure water from the DS. However, producing pure water from the diluted DS requires a separation process such as a FO-hybrid process [3]. One of the common approaches suggested is using established membrane based processes such as RO [4] and/or nanofiltration (NF) [5] as post-treatment processes to separate and regenerate draw solutes for potable water desalination.

Based on recent studies, FO-hybrid systems could be more effective when the water treatment involves highly challenging waters such as highly impaired water sources from drilling flow back water [6,7], produced water from oil and gas extraction [8], brine treatment [9], raw sewage treatment [10], and aerobic osmotic membrane bioreactor [11,12].

Fertiliser driven FO (FDFO) process is seen as a practical application of the FO process [13,14]. The diluted fertiliser DS from the FO process, which contains essential nutrients for plants, can be used for fertigation of crops if the nutrient concentration in the diluted DS meets required standards. The final diluted fertiliser concentrations that come out of the FO process, however, depend on the concentration level of the feed water at which they reach osmotic equilibrium [15]. This becomes a challenge when feed water sources with higher salinities are used, where the diluted fertiliser DS concentration does not meet the maximum nutrient concentration levels for direct fertigation. An easy solution is further dilution using available freshwater sources; however, this option is only practical when fresh water sources are available. The second option to dilute the fertiliser concentrations beyond osmotic equilibrium is a pressure assisted FDFO process to generate additional flux that could help further dilution of the fertiliser DS [16]. Another option studied by this group has been the FDFO-NF hybrid system where NF is used as a post-treatment to reduce the fertiliser concentration by removing the excess fertiliser from the diluted fertiliser DS and recovering it for further reuse [17]. The NF permeate, which is a more diluted fertiliser solution can then be applied for direct fertigation of crops. Recently, the FDFO-NF system has been studied at a pilot-scale level by our group [13,18].

The main objective of this study is therefore to conduct simulation of a full-scale FDFO-NF hybrid system to study how the various process parameters in the hybrid system affect each other when operated in a continuous closed-loop system based on a simple mass balance of the volumetric flows, draw solutes and the feed solutes. This study provides an enhanced understanding of some of the options and limitations of operating a full-scale FDFO-NF hybrid or in any FO-NF or FO-RO in a continuous closed-loop system. This study however does not include the process and energy efficiencies of the FO-NF hybrid system, as this particular area is being considered in a separate study.

2. Mass balance simulation of a continuous closed-loop FO-NF system

The summary of the mass balance for the two types of flows (DS & FS), draw solutes and feed solutes for a full-scale FDFO-NF hybrid system is presented in Fig. 1. The simulation is entirely based on the ideal mass balance model in a closed system and which occurs independent

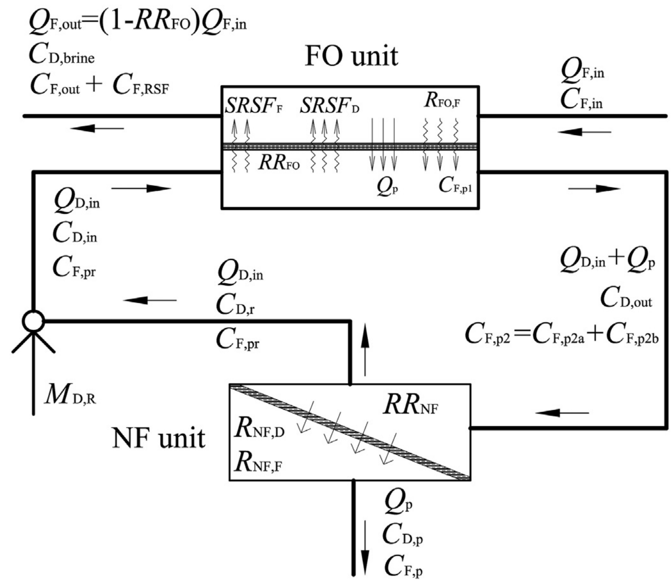

Fig. 1. Schematic layout of a continuous closed-loop FO-NF hybrid system considering the mass balance for the two flow rates, draw solutes and the feed solutes. For simulation mass concentrations (C) are measured in g L^{-1}, flow rate or capacity Q in m^3 day^{-1}, rejection (R) and recovery rates (RR) in %.

of the process performances such as water flux (assuming infinite membrane area) including performance mechanisms. Therefore, the simulation models used in this study, especially related to the mass balance on the draw solutes and feed solutes, do not take into consideration the non-idealities that may exist in a real process and therefore assuming FO or NF modules as a black box. The only membrane properties accounted in this simulation models are the rejection rates and recovery rates of both the FO and NF membranes. Reasonable fixed rejection rates of the FO and NF membranes have been assumed for simulation although in reality, these rejection rates could slightly vary depending on its operating conditions under which the membrane is subjected.

2.1. Mass balance for the solution flows

Considering a steady flow with no net build-up of volume in a continuous closed-loop FO-NF hybrid system (Fig. 1), the FO permeate and the NF permeate flow rates should be the same as the FO-NF plant capacity Q_p which can be expressed as follows:

$$Q_p = RR_{FO}\,Q_{F,in} \tag{1}$$

where $Q_{F,in}$ and RR_{FO} are the inlet feed flow rates and feed recovery rate of the FO unit.

If $Q_{D,in}$ is the initial DS flow rate at the FO inlet, then the diluted DS flow rate at the FO outlet becomes ($Q_{D,in} + Q_p$). The initial DS flow rate, however, is the same as the NF concentrate flow rate (i.e. no net accumulation in the system), referred to as the recycled DS in this study, and is given as a function of NF recovery (RR_{NF}) rate as follows:

$$Q_{D,in} = Q_p\left(\frac{1}{RR_{NF}} - 1\right) \tag{2}$$

2.2. Mass balance for the draw solutes

Solute transfer in a FO process occurs in both the directions: forward diffusion of feed solutes and reverse diffusion of draw solutes. The reverse solute flux (RSF) measures the rate of reverse diffusion of draw solutes towards FS during the FO process. Since both RSF and water flux change with the DS concentration, the rate of reverse diffusion is

Please cite this article as: S. Phuntsho, et al., A closed-loop forward osmosis-nanofiltration hybrid system: Understanding process implications through full-scale simulation, Desalination (2016), http://dx.doi.org/10.1016/j.desal.2016.12.010