Journal of Membrane Science 537 (2017) 22–31

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Evaluation of fertilizer-drawn forward osmosis for coal seam gas reverse osmosis brine treatment and sustainable agricultural reuse

Youngjin Kim[a,b], Yun Chul Woo[b], Sherub Phuntsho[b], Long D. Nghiem[c], Ho Kyong Shon[b,*], Seungkwan Hong[a,*]

[a] School of Civil, Environmental and Architectural Engineering, Korea University, 145, Anam-ro, Seongbuk-Gu, Seoul 02841, Republic of Korea
[b] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney (UTS), PO Box 123, Broadway, NSW 2007, Australia
[c] Strategic Water Infrastructure Laboratory, School of Civil Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

ARTICLE INFO

Keywords:
CSG produced water
Fertilizer-drawn forward osmosis
Specific energy consumption
FDFO simulation
Membrane cleaning

ABSTRACT

The fertilizer-drawn forward osmosis (FDFO) was investigated for treating coal seam gas (CSG) produced water to generate nutrient rich solution for irrigation. Its performance was evaluated and compared with reverse osmosis (RO) in terms of specific energy consumption (SEC) and nutrient concentrations in the final product water. The RO-FDFO hybrid process was developed to further improve FDFO. The results showed that FDFO has the lowest SEC followed by the RO-FDFO and RO processes. The final nutrient concentration simulation demonstrated that the RO-FDFO hybrid process has lower final concentration, higher maximum recovery and lower nutrient loss than the stand alone FDFO process. Therefore, it was suggested that the RO-FDFO is the most effective treatment option for CSG produced water as well as favourable nutrient supply. Lastly, membrane fouling mechanism was examined in CSG RO brine treatment by FDFO, and the strategies for controlling fouling were critically evaluated. KNO_3 exhibited the highest flux decline corresponding to the highest reverse salt flux, while the most severe membrane scaling was observed with calcium nitrate, primarily due to the reverse transport of calcium ions. To control membrane fouling in FDFO process, both physical flushing and chemical cleaning were examined. Membrane cleaning with citric acid of 5% resulted in a complete flux recovery.

1. Introduction

Coal seam gas (CSG), which is also known as coal-bed methane, has been widely explored in United States, Australia, Canada, United Kingdom, and other nations since the 1970s [1]. During CSG extraction, underground water in the coal seam is pumped to the surface together with methane gas. This is often called CSG produced water, which is dominantly composed of sodium, chloride and bicarbonate [2]. In Australia, the salinity of CSG produced water is relatively low, typically in the range of up to 6000 mg/L [3]. Thus, CSG produced water can be treated and utilized for a variety of application including irrigation [4]. Since CSG produced water has a high sodium content (i.e. a high sodium adsorption ratio), utilization of untreated CSG produced water for irrigation can lead to a gradual decrease in the permeability of soil, eventually causing infiltration problems and other form of soil degradation [5]. Therefore, it is necessary to remove sodium to enable reuse of CSG produced water for irrigation.

Reverse osmosis (RO) is currently the most widely used technology for CSG produced water treatment (Fig. 1**a)** due to its several merits such as small footprint, ease of automation, and modular design [6]. However, RO generally exhibits high energy consumption (i.e., typically above 4–5 kWh/m^3 for a seawater desalination plant) due to the high hydraulic pressure as a driving force [7,8]. Moreover, RO is often hampered by high fouling potential and inherent limitations such as low recovery [9,10]. To overcome these issues, forward osmosis (FO) was proposed since it can provide high rejection of contaminants, low fouling propensity, high fouling reversibility and low energy requirement [11,12]. However, FO has several limitations including the need to extract pure water from the diluted draw solution (DS), requiring the additional desalting processes (e.g., nanofiltration (NF), RO or mem-

Abbreviations: CAN, Calcium nitrate; CSG, Coal seam gas; DAP, Di-ammonium phosphate; DI, Deionized; DS, Draw solution; EDTA, Ethylenediaminetetraacetic acid; EDX, Energy dispersive x-ray spectroscopy; FDFO, Fertilizer-drawn forward osmosis; FO, Forward osmosis; FS, Feed solution; FSF, Forward salt flux; ICP, Internal concentration polarization; NF, Nanofiltration; OMBR, Osmotic membrane bioreactor; PA, Polyamide; RO, Reverse osmosis; SEM, Scanning electron microscopy; SOA, Ammonium sulphate; RSF, Reverse salt flux; SEC, Specific energy consumption; SRSF, Specific reverse salt flux; TFC, Thin-film composite; XRD, X-Ray diffraction

* Corresponding authors.
E-mail addresses: Hokyong.Shon-1@uts.edu.au (H.K. Shon), skhong21@korea.ac.kr (S. Hong).

http://dx.doi.org/10.1016/j.memsci.2017.05.032
Received 10 November 2016; Received in revised form 13 April 2017; Accepted 7 May 2017
Available online 08 May 2017
0376-7388/

Nomenclature

A	Water permeability coefficient
B	Salt permeability coefficient
$C_{D,i}$	Maximum DS concentration
$C_{D,f}$	Final DS concentration having equal osmotic pressure with the initial FS concentration
$C_{nut,f}$	Nutrient concentration in the final produced water
J_s	Reverse salt flux
J_w	Water flux
$Loss_{Draw}$	Draw solute loss at the maximum recovery rate in FDFO
M_w	Molecular weight of DS
n	Number of species
P_D	Draw pressure (bar)
P_F	Feed pressure (bar)
Q_D	Draw flow rate (m^3/h)
Q_F	Feed flow rate (m^3/h)
$Q_{P,FDFO}$	Permeate flow rate (m^3/h) in FDFO
$Q_{P,RO}$	Permeate flow rate (m^3/h) in RO
$Q_{P,total}$	Total permeate flow rate (m^3/h)
$Ratio_{nut}$	Ratio of each nutrient component
R_{max}	Maximum recovery rate in FDFO
R_g	Universal gas constant
S	Structure parameter of the support layer
SEC_{FDFO}	Specific energy consumption of FDFO
SEC_{RO}	Specific energy consumption of RO
$SEC_{RO+FDFO}$	Specific energy consumption of the RO-FDFO hybrid process
$SRSF$	Specific reverse salt flux
T	Temperature
$V_{D,i}$	Initial DS volume
$V_{D,f}$	Final DS volume
V_{ext}	Water extraction capacity

Greek symbol

η	Pump efficiency

brane distillation) [13,14].

Recently, fertilizer-drawn forward osmosis (FDFO) has received increased attention since the diluted fertilizer solution can be utilized directly for irrigation purpose and thus the diluted DS separation and recovery process is not required [15–17]. However the diluted fertilizer solution still required substantial dilution since the final nutrient concentration can exceed the standard nutrient requirements for irrigation especially using feed water sources with high salinity [16,17]. Thus, NF can be employed as a post-treatment process for further dilution and in meeting the water quality requirements for fertigation [15]. However, FDFO is seen to be more suitable for the treatment of low salinity impaired water sources (e.g., CSG produced water, wastewater and so on) as shown in Fig. 1**b** so that desired fertilizer dilution can be achieved without the need of a NF post-treatment process [18].

Since FDFO utilizes highly concentrated fertilizer DS, FDFO has serious problems regarding the reverse solute flux of the draw solute induced by the large concentration differences between the feed solution (FS) and DS across FO membrane. The reverse diffusion of draw solutes to FS in the FDFO process can reduce the recovery rate and lose the valuable fertilizers in DS. In addition, reverse salt flux (RSF), which is reversely diffused draw solute through FO membrane from DS to FS, can alter the feed chemistry and accelerate membrane fouling or scaling [19–21], and inhibit the biological processes in osmotic membrane bioreactor (OMBR) which is one of the potential applications [18,22]. Moreover, because of an increase in FS concentration caused by RSF, direct discharge of FS may entail negative impacts to the environment [23], which requires further treatment of FS concentrate.

In order to solve or mitigate these problems (i.e., high energy consumption in RO and valuable fertilizer draw solute loss by RSF in FDFO), a RO-FDFO hybrid process was proposed for simultaneous CSG produced water treatment and the agricultural application based on the concept described in Fig. 1**c**. This hybrid system consists of two parts (i.e., RO and FDFO). The 1st stage RO will concentrate CSG produced water by up to 75% and produce clean water. Then, the 2nd stage FDFO will treat CSG RO brine from the 1st stage RO and also produce nutrient

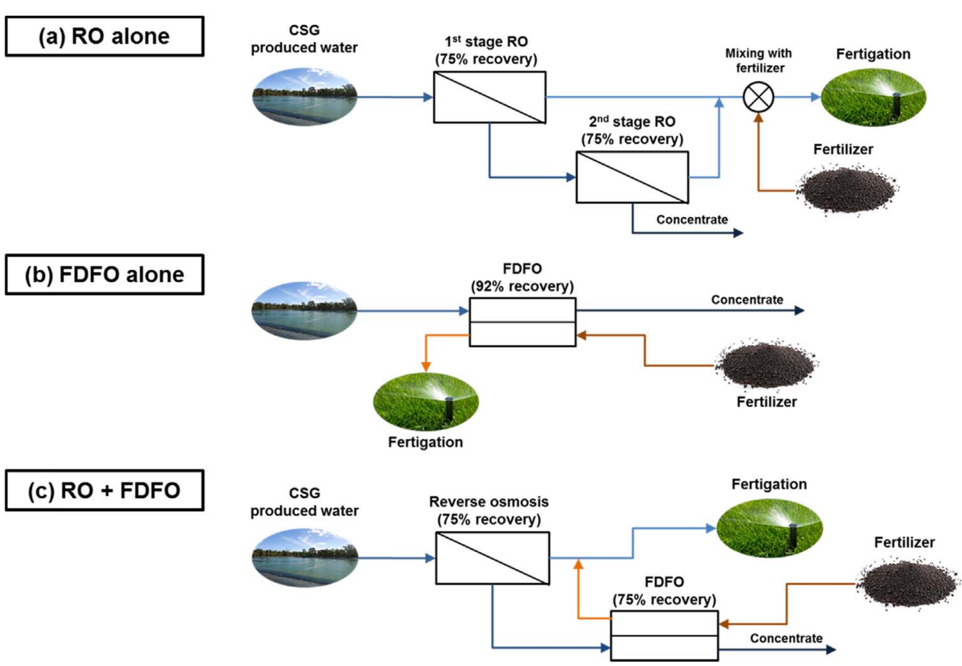

Fig. 1. Conceptual process layout for integrating RO-FDFO hybrid process: (a) 2 stage RO system, (b) FDFO alone system and (c) RO-FDFO hybrid system.