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Application of volume-retarded osmosis and low-pressure membrane hybrid process for water reclamation

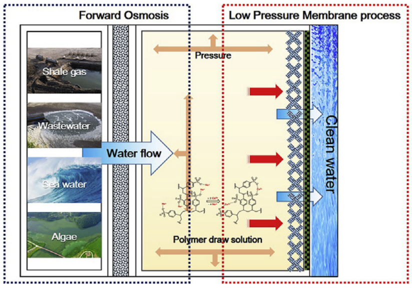
Sung-Ju Im [a], Jungwon Choi [a], Jung-Gil Lee [b], Sanghyun Jeong [a, **], Am Jang [a, *]

[a] Graduate School of Water Resources, Sungkyunkwan University (SKKU), 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi-do 16419, Republic of Korea
[b] King Abdullah University of Science and Technology (KAUST), Water Desalination and Reuse Center (WDRC), Biological and Environmental Science & Engineering (BESE), Thuwal 23955-6900, Saudi Arabia

HIGHLIGHTS

- New energy saving forward osmosis-low pressure membrane hybrid process was tested.
- The system could produce final product with an increase in inner pressure of tank.
- A polymeric draw solute was effective in the operation of this hybrid system.
- A mass balance modeling was used for optimization.
- An applicability of this hybrid process in wastewater treatment was confirmed.

GRAPHICAL ABSTRACT



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ABSTRACT

A new concept of volume-retarded osmosis and low-pressure membrane (VRO-LPM) hybrid process was developed and evaluated for the first time in this study. Commercially available forward osmosis (FO) and ultrafiltration (UF) membranes were employed in a VRO-LPM hybrid process to overcome energy limitations of draw solution (DS) regeneration and production of permeate in the FO process. To evaluate its feasibility as a water reclamation process, and to optimize the operational conditions, cross-flow FO and dead-end mode UF processes were individually evaluated. For the FO process, a DS concentration of 0.15 g mL^{-1} of polysulfonate styrene (PSS) was determined to be optimal, having a high flux with a low reverse salt flux. The UF membrane with a molecular weight cut-off of 1 kDa was chosen for its high PSS rejection in the LPM process. As a single process, UF (LPM) exhibited a higher flux than FO, but this could be controlled by adjusting the effective membrane area of the FO and UF membranes in the VRO-LPM system. The VRO-LPM hybrid process only required a circulation pump for the FO process. This led to a decrease in the specific energy consumption of the VRO-LPM process for potable water production, that was similar to the single FO process. Therefore, the newly developed VRO-LPM hybrid process, with an appropriate DS selection, can be used as an energy efficient water production method, and can outperform conventional water reclamation processes.

1. Introduction

Membrane technology is currently considered to be the most promising alternative for conventional water treatment technologies (Guo et al., 2012). This is because membrane technology has a

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* Corresponding author.
** Corresponding author.
E-mail addresses: sh.jeong@skku.edu (S. Jeong), amjang@skku.edu (A. Jang).

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shorter treatment time, higher rejection rate, and more economical values (smaller footprint requirement, and easier operation) than conventional methods (Kim and Jang, 2017; Arhin et al., 2016). Various types of membrane technologies are recently being used in water and wastewater treatment (Holloway et al., 2016; Kim et al., 2017; Jeong et al., 2013; Qin and He, 2014).

Of all the membrane processes, the forward osmosis (FO) process has gained increasing attention in the areas of industrial water treatment and desalination, because its operating force is different from that of the pressure-driven membrane process. The FO process is driven by the natural osmotic pressure difference between the feed solution (FS) and the draw solution (DS), and can, therefore, be operated without additional hydraulic pressure. The FO process can remove a wide range of pollutants, and has a lower fouling propensity, higher reversibility, and lower chemical cleaning frequency than a pressure-driven membrane process (Kim et al., 2007; Holloway et al., 2014; Cath et al., 2010). However, FO processes have their own inevitable drawbacks, such as membrane fouling, DS regeneration, concentration polarization (CP) phenomenon, and short membrane life (Agarwal et al., 2011; Molinari et al., 2008; Cui and Choo, 2014). These drawbacks have a direct impact on the capital expenditure (CAPEX) and operating expenditure (OPEX) of the FO process (Gwak et al., 2015; Wang et al., 2011; Go et al., 2016). The most relevant problem regarding cost and energy in the FO process is the limitation of the DS, which is essential for the FO process. Numerous studies have been conducted to find an appropriate DS, as well as to overcome the DS regeneration problem. Recent research on DS has focused on the synthesis of DS using various new materials, or applying a DS that does not need to be regenerated (i.e., fertilizer and seawater) (Huang et al., 2017; Hau et al., 2014; Ge et al., 2013; Chekli et al., 2017). A further research area is that of hybrid technologies, which produce energy or utilize natural energy sources, such as solar heat, tidal power, wind, or geothermal heat to increase energy efficiency in the membrane process (Go et al., 2016; Valladares Linares et al., 2014; Yang et al., 2015; Xie et al., 2016). However, these have limitations for immediate industry-scale applications, as they require additional technology or are still under development (Chung et al., 2012; Turek et al., 2017).

In this regard, a volume-retarded osmosis (VRO) and low-pressure membrane (LPM) hybrid process (VRO-LPM) has recently been developed by our research group. This concept originated from the principle of the pressure-retarded osmosis (PRO) process, that generated electricity as the DS volume increased. In both the VRO and PRO (or even FO) processes, the permeate moves from the FS side (low concentration) to the DS side (high concentration) owing to the difference in osmotic pressure, and the volume of the DS increases due to the migrating permeate (Zhao et al., 2012; Nagy, 2014; Fortunato and Leiknes, 2017). In the PRO process, however, high-pressure pumps are required to meet the minimum energy requirement for converting the potential energy generated by the increased DS to electrical energy, which is the first point of difference from the VRO-LPM process. In the case of VRO-LPM, the increased DS volume, resulting from the FO process, increases the inner pressure of the closed DS tank, and is a driving force for the LPM part of this hybrid process. Therefore, the main aim of the VRO-LPM process is to minimize the energy consumption of the water treatment process that is typically required in the LPM process to produce final permeate and regenerate the DS. In addition, because the inner pressure is being used directly, the required installation area for the FO-LPM is smaller than for typical FO hybrid systems (i.e., FO-nanofiltration (NF), FO-reverse osmosis (RO)). The two processes (FO and NF) are typically driven separately in the FO-NF process. In this case, operation and maintenance are complex, and continuous cleaning (both physical and chemical) is also required for both membrane processes. However, the VRO-LPM process only uses the principle of the FO process, which makes the system both simpler and cheaper than other hybrid processes, while also being attractive for application in developing countries.

To develop the VRO-LPM hybrid process, two conditions need to be satisfied to make it fully operational. First, because the DS must be filtered with high rejection by the LPM, a polymeric DS is recommended. The polymeric DS must satisfy the following criteria: i) non toxicity; ii) high solubility; iii) low viscosity; iv) low cost; v) high reusability; vi) low reverse salt (or solute) flux (RSF); and vii) high osmotic pressure in the solution phase (Tian et al., 2015; Luo et al., 2014). Secondly, the water flux of the FO process is relatively higher than that of the LPM process to maintain an appropriate internal pressure of the DS tank and meet the mass balance.

The main objective of this study was, therefore, to evaluate the feasibility and applicability of the VRO-LPM hybrid process, an energy saving water reclamation process. Three experimental steps (evaluation, modeling, and application) were performed. First, the individual performances of the FO and LPM processes were evaluated as inputs for the design of a VRO-LPM hybrid process. During the evaluation, different concentrations of DS and molecular weight cut-off (MWCO) of the LPM, RSF, of FO processes, and solute rejection of the LPM process were considered. Secondly, a mass balance modeling based on the database obtained from the individual membrane tests, was conducted to study the possibility and feasibility of the VRO-LPM hybrid process. Lastly, the performance of the VRO-LPM hybrid process was tested in the treatment of real secondary wastewater effluent (SWWE).

2. Materials and methods

2.1. Experimental setup

To evaluate the performance of single FO and LPM processes and the VRO-LPM hybrid process, three different experimental setups were required (Fig. 1).

2.1.1. Single FO process

First, an FO process was used to evaluate the performance of the single FO process (Fig. 1a). A single FO process comprises FS and DS tanks, two gear pumps, a customized cross-flow FO cell (7.7 cm long, 2.6 cm wide, and 0.3 cm deep), and a chiller (CPT Inc., Korea). A digital balance (Sartorius, ED623S, Goettingen, Germany) was installed under the DS tank to calculate the flux values by measuring the increase in DS weight. The effective membrane area was 20.02 cm^2. The flow rate and temperature of each solution were fixed at 400 mL min^{-1} (cross flow velocity: 8.5 cm s^{-1}) and 25 ± 1 °C, respectively. The process was conducted in FO mode (active layer facing the FS), and the initial volume of each solution was 1 L. To evaluate the performance in terms of water flux (J_W, $L \cdot m^{-2} \cdot h^{-1}$ (LMH)), the following equation was used.

$$J_w = \frac{\Delta V}{A \Delta t} \tag{1}$$

where, ΔV is the weight change, Δt is the time interval, and A is the effective membrane area. RSF (J_s, $g \cdot m^{-2} \cdot h^{-1}$ (GMH)), was determined by converting the conductivity and total organic carbon (TOC) values of PSS by using Eq. (2).

$$J_s = \frac{\Delta(C_t V_t)}{A \Delta t} \tag{2}$$