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Scale-up of osmotic membrane bioreactors by modeling salt accumulation and draw solution dilution using hollow-fiber membrane characteristics and operation conditions

Suhan Kim *

Department of Civil Engineering, Pukyong National University, 365 Sinseonro, Nam-gu, Busan 608-739, Republic of Korea

HIGHLIGHTS

- The full-scale OMBR model simulates salt accumulation and draw solution dilution.
- The model helps us to select better FO membrane with higher water flux propensity.
- Water flux in full-scale OMBR is much smaller than that in lab-scale tests.
- External concentration polarization adversely affects water flux considerably.
- The full-scale OMBR operation with a long SRT is limited.

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ABSTRACT

A full-scale osmotic membrane bioreactor (OMBR) model was developed to simulate salt accumulation, draw solution (DS) dilution, and water flux over the hollow-fiber membrane length. The model uses the OMBR design parameters, DS properties, and forward osmosis (FO) membrane characteristics obtained from lab-scale tests. The modeling results revealed a tremendous water flux decline (10 → 0.82 LMH) and short solids retention time (SRT: 5 days) due to salt accumulation and DS dilution when OMBR is scaled up using commercially available DS and FO membrane. Simulated water flux is a result of interplay among reverse salt flux, internal and external concentration polarization (ICP and ECP). ECP adversely impacts water flux considerably in full-scale OMBR although it is often ignored in previous works. The OMBR model makes it possible to select better DS properties (higher flow rate and salt concentration) and FO membranes with higher water flux propensity in full-scale operation.

1. Introduction

Osmotic membrane bioreactor (OMBR) is a combination of a conventional membrane bioreactor (MBR) with forward osmosis (FO) membrane in a biological tank. Since the concept of OMBR is introduced very recently (Achilli et al., 2009), the researches on OMBR focused on the lab-scale experiments to elucidate the fundamentals in OMBR such as: (1) the excellent selectivity of FO membrane in OMBR for various pollutants (Alturki et al., 2012); (2) the fouling propensity of FO membrane in OMBR (Achilli et al., 2009; Hanmin et al., 2012; Zhang et al., 2012; Qiu and Ting, 2014); (3) the biological activity in OMBR (Qiu and Ting, 2013); and (4) the draw salts for OMBR (Bowden et al., 2012).

OMBR has three unique characteristics as a wastewater treatment process as followings: (1) a biological process, (2) a physicochemical process with high selectivity for both organic and inorganic pollutants, and (3) an energy efficient process. As a biological process, OMBR needs a long solids retention time (SRT) for lower sludge production for disposal and the removal of slow-to-grade organic matters and persistent organic pollutants (Chen et al., 2012). The accumulated dissolved organic matters due to the high retention property of the FO membrane may lead to enhanced biological degradation of recalcitrant organics, reduced dissolved organic content in the effluent, and enhanced removal of micropollutants (Yap et al., 2012). However, the high retention property of OMBR could in turn inhibit microbial activity of microorganism due to accumulated salts. As a physicochemical process, the high selectivity of FO membrane for pollutants from feed wastewater has already been reported in literatures (Alturki et al., 2012; Bowden et al., 2012; Chen et al., 2012; Zhang et al., 2012), which

* Tel.: +82 51 629 6065; fax: +82 51 629 6063.
E-mail address: suhankim@pknu.ac.kr

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is a very strong point to emphasize the bright prospect of OMBR. Especially micro-pollutants including metals and less polar organic matters can be more efficiently removed by FO membranes for OMBR than microfiltration (MF) membranes for convention MBR (Yap et al., 2012). As an energy efficient process, OMBR uses mechanical pressure lower than conventional MBR but water flux in a full-scale system should be reasonable, which implies that OMBR flux should be in the range of MBR flux (*e.g.*, 10–30 LMH reported by Lay et al., 2010). So far, the full-scale operation of OMBR with reasonable hydraulic retention time (HRT) and solids retention time (SRT) is hardly reported. Thus, it can be said that the feasibility of OMBR as a full-scale application has not been verified yet.

OMBR has a critical problem. Because of high selectivity of FO membrane, salts are retained and accumulated in the bioreactor. Another source of the salt accumulation is highly concentrated draw solution (DS). Salts in DS diffuse to the bioreactor by the concentration difference between DS and feed, which is called reverse salt flux. The salt accumulation diversely affects the bioactivity of microbes in OMBR (Qiu and Ting, 2013) and the water flux through FO membrane (Xiao et al., 2011). The work by Xiao et al. (2011) was to simulate the salt accumulation in OMBR, which was the first systematic research to elucidate the mechanisms of salt accumulation in OMBR. There have been no published results related to the OMBR modeling work since it has been published in 2011 to the author's best knowledge. Reflecting the effect of internal concentration polarization (ICP), the salt accumulation model simulated water and reverse salt fluxes due to salt accumulation in the bioreactor using FO membrane characteristics and OMBR operation conditions. Although the effects of external concentration polarization (ECP) and DS dilution are not considered, their work gives an insight to design and operate OMBR process (Xiao et al., 2011).

However, ECP and DS dilution are inevitable in full-scale OBMR process because ECP exists even in the turbulent flow (Tan and Ng, 2008) and DS should be gradually diluted as it flows in the DS channel. In addition, the DS salt concentration is a function of longitudinal position from the inlet of DS channel because of gradually diluted DS, and thus local variations in osmotic pressures, water flux, and reverse salt flux occur. With no consideration of the effects of ECP and DS dilution, the modeled salt accumulation must be underestimated, which motivated the author to carry out this work.

The objective of this work is to develop a full-scale OMBR model reflecting the effects of ICP, ECP, and reverse salt flux. Fouling phenomenon and biological activities are not considered in this work. The full-scale OMBR model is to simulate salt accumulation, local variations in DS dilution and water flux in hollow-fiber FO membranes. The parameters used in the model are the OMBR design parameters (HRT, SRT, feed flow rate and salt concentration), DS properties (DS flow rate and salt concentration), and FO membrane characteristics (water and salt permeability; resistance to salt diffusion within the support layer; and the length and inner diameter of a hollow fiber). The model was verified by lab-scale experimental data obtained from two different literatures (Xiao et al., 2011; Cornelissen et al., 2008). The full-scale OMBR model will be used not only to evaluate the applicability of current small-scale OMBR technologies developed in the laboratory to full-scale operations, but also to suggest better strategies to enhance the performance of full-scale OMBR.

2. Methods

2.1. Mass balance in full-scale OMBR

Full-scale OMBR considered in this study has a bundle of hollow-fiber FO membranes submerged in the bioreactor (Fig. 1a). Feed wastewater flows into the bioreactor with a flow rate (Q_f) and a salt concentration (C_f). Pure water penetrates through the hollow-fiber FO membranes, and salts, organic matters, and microbes are retained and accumulated in the bioreactor. These concentrated materials (*i.e.*, sludge) are discharged with a flow rate (Q_s) and a salt concentration (C_s). Continuous aeration in the bioreactor may result in complete mixing of salts, and the salt concentrations in the sludge (C_s) and the bioreactor (C_R) are thus assumed to be identical. Draw solution (DS) enters the inside of the hollow-fiber membrane channel with a flow rate (Q_d) and a salt concentration (C_d) to make osmotic pressure difference between the inside and the outside (*i.e.*, the bioreactor) of the hollow-fibers. Drawing pure water out of feed wastewater via FO membrane, DS becomes diluted and is discharged from OMBR with a flow rate (Q_{dd}) and a salt concentration (C_{dd}). At a steady state, mass balance for water and salts in the bioreactor are described as:

$$Q_f + Q_d = Q_s + Q_{dd} \quad (1)$$

$$Q_f C_f + Q_d C_d = Q_s C_R + Q_{dd} C_{dd} \quad (2)$$

The hydraulic retention time (HRT; θ_{HRT}) and the solids retention time (SRT; θ_{SRT}) for full-scale OMBR system are defined by:

$$\theta_{HRT} = V_R / Q_f \quad (3)$$

$$\theta_{SRT} = \frac{C_R V_R}{C_s Q_s} = \frac{V_R}{Q_s} (C_R = C_s) \quad (4)$$

where V_R is the bioreactor volume determined by given feed flow rate (Q_f) and HRT (θ_{HRT}). The two variables (C_R) and (C_{dd}) represent salt accumulation and DS dilution in OMBR, respectively. They can be calculated using water and reverse salt fluxes through FO membrane.

Mass balance for water and salts in a hollow-fiber should be considered first to find the water and reverse salt fluxes through the FO membrane. Water flows from the bioreactor (the feed side)

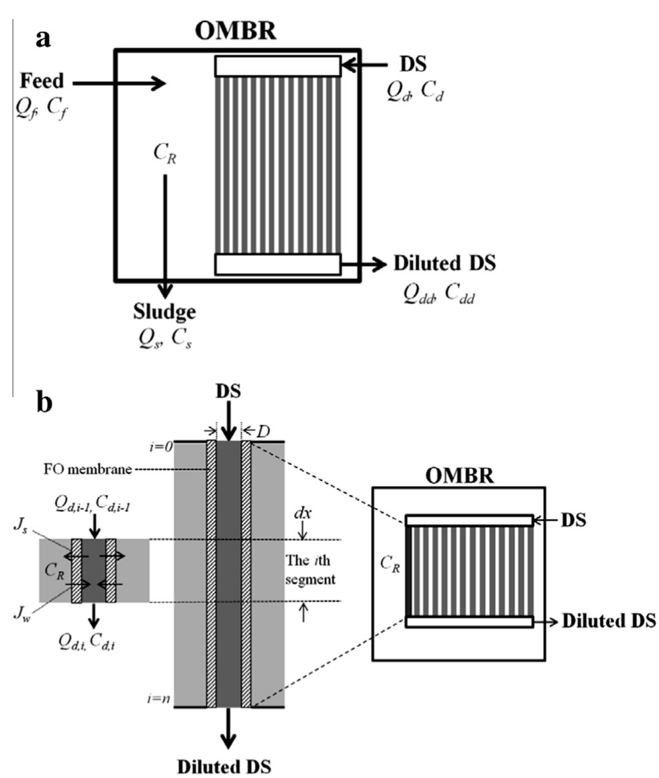

Fig. 1. Mass balance (a) in full-scale OMBR and (b) in the hollow-fiber FO membrane.

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