Water Research 93 (2016) 133–140

Contents lists available at ScienceDirect

Water Research

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

Optimization of gravity-driven membrane (GDM) filtration process for seawater pretreatment

Bing Wu [a,*], Florian Hochstrasser [b], Ebrahim Akhondi [a], Noëmi Ambauen [c], Lukas Tschirren [b], Michael Burkhardt [b], Anthony G. Fane [a,d], Wouter Pronk [e,**]

[a] Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Cleantech Loop, CleanTech One #06-08, 637141, Singapore
[b] Institute of Environmental and Process Engineering, HSR University of Applied Sciences Rapperswil, Oberseestrasse 10, 8640 Rapperswil, Switzerland
[c] Institute of Environmental Engineering, ETH Zürich, 8093 Zürich, Switzerland
[d] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[e] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Duebendorf, Switzerland

ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form
10 February 2016
Accepted 11 February 2016
Available online 15 February 2016

Keywords:
Biofilm layer
Gravity-driven membranes
Optical coherence tomography (OCT)
Seawater pretreatment
Stabilized flux

ABSTRACT

Seawater pretreatment by gravity-driven membrane (GDM) filtration at 40 mbar has been investigated. In this system, a beneficial biofilm develops on the membrane that helps to stabilize flux. The effects of membrane type, prefiltration and system configuration on stable flux, biofilm layer properties and dissolved carbon removal were studied. The results show that the use of flat sheet PVDF membranes with pore sizes of 0.22 and 0.45 μm in GDM filtration achieved higher stabilized permeate fluxes (7.3–8.4 L/m^2h) than that of flat sheet PES 100 kD membranes and hollow fibre PVDF 0.1 μm membranes. Pore constriction and cake filtration were identified as major membrane fouling mechanisms, but their relative contributions varied with filtration time for the various membranes. Compared to raw seawater, prefiltering of seawater with meshes at sizes of 10, 100 and 1000 μm decreased the permeate flux, which was attributed to removal of beneficial eukaryotic populations. Optical coherence tomography (OCT) showed that the porosity of the biofouling layer was more significantly related with permeate flux development rather than its thickness and roughness. To increase the contact time between the biofilm and the dissolved organics, a hybrid biofilm-submerged GDM reactor was evaluated, which displayed significantly higher permeate fluxes than the submerged GDM reactor. Although integrating the biofilm reactor with the membrane system displayed better permeate quality than the GDM filtration cells, it could not effectively reduce dissolved organic substances in the seawater. This may be attributed to the decomposition/degradation of solid organic substances in the feed and carbon fixation by the biofilm. Further studies of the dynamic carbon balance are required.

1. Introduction

Seawater reverse osmosis (SWRO) desalination as an alternative supply of high-quality drinking water is receiving global attention. However, compared to surface and groundwater RO processes, SWRO requires much more energy (Pearce, 2008). The energy consumption of RO membrane filtration is associated with the osmotic pressure of the feed and the recovery (the ratio of product flow and feed flow). Thermodynamics dictate the minimum energy for desalination, and major efforts have been made in SWRO to approach this minimum. In the desalination process, additional energy is required for intake, pretreatment, posttreatment, and brine discharge stages. It has been noted that the energy demand for pretreatment of raw seawater accounts for the majority of the ancillary energy used (Elimelech and Phillip, 2011) and provides an opportunity for meaningful reduction of the overall system energy.

The primary goal of seawater pretreatment is to remove particles and reduce organics in the seawater feed, which will cause less fouling in the RO process. Although conventional pretreatment processes (e.g., coagulation, dissolved air flotation, and media filtration) have been widely used for SWRO due to their moderate

* Corresponding author.
** Corresponding author.
E-mail addresses: wubing@ntu.edu.sg (B. Wu), wouter.pronk@eawag.ch (W. Pronk).

http://dx.doi.org/10.1016/j.watres.2016.02.021

energy consumption, they typically consume chemicals and produce quality of the treated seawater that often is not satisfactory. This can lead to higher cleaning frequency and replacement of RO membranes. In addition, stable RO operation may not be guaranteed with poor or variable quality seawater (Greenlee et al., 2009; Pearce, 2008). The improved pretreatment achievable by low pressure membranes has been recognized for some time (Pearce, 2008), and includes microfiltration (MF) (Bae et al., 2011), ultrafiltration (UF) (Huang et al., 2011), while even nanofiltration (NF) was considered as a suitable pretreatment (Kaya et al., 2015). However, these pressure-driven membrane filtration processes also require effective fouling control strategies (such as cross-flow, backwashing, and/or air scouring etc.) (Akhondi et al., 2014), which contribute significant energy demand to the overall desalination process (Knops et al., 2007).

Gravity-driven membrane filtration (GDM), which was initially developed as a low energy process to treat different surface waters and diluted wastewaters (Derlon et al., 2013, 2012; Peter-Varbanets et al., 2012, 2010, 2011, 2009), has also shown promise as a seawater pre-treatment process with less energy and chemical cleaning (Akhondi et al., 2015). In the GDM filtration process, the feed is under a gravity pressure of 40–100 mbar and is applied without crossflow to the membranes. Over time a biofilm develops on the membrane that arrests further fouling and leads to a stabilized permeate flux. It has been shown that the bacterial community utilizes the organic substances in the feed seawater for their growth and augmentation to form biofouling layers on the membrane, while the movement and predation behaviour of eukaryotic organisms in the biofouling layer produce an open and spatially heterogeneous structure (Akhondi et al., 2015; Derlon et al., 2013, 2012; Klein et al., 2016). The GDM process consumes only about 3–10% of the energy used in conventional UF pretreatment (Akhondi et al., 2015), however, its permeate flux (3.6–7.3 L/m^2h) is almost an order of magnitude less than that of conventional UF pretreatment (Xu et al., 2012). The trade-off lies in more membranes required to achieve the same productivity. Therefore, there is an incentive to seek improvements in permeate flux without significant added energy input and capital cost.

Our previous work on GDM filtration of seawater (Akhondi et al., 2015) showed the following: (i) higher temperatures improved permeate flux during GDM filtration of seawater. This can be attributed to lower viscosity, increased bacterial metabolism and the presence of eukaryotic organisms that have greater predation activity at higher temperatures, leading to the formation of more porous biofouling layers. (ii) A higher hydrostatic pressure also provides an increased permeate flux thanks to the greater driving force. However, this strategy is limited if the goal is to avoid increased energy demand and capital cost. The influences of other operating parameters on the permeate flux of the GDM filtration process for seawater pretreatment have not been investigated to date.

In this study, we focus on optimization of the GDM process by assessing the productivity and permeate quality over a range of operating conditions (such as membrane type and prefiltration strategy). To further improve permeate flux and quality, we also investigated a combined biofilm reactor with a submerged GDM filtration system, in which biofilm carriers facilitated the increase in biovolume and retention time of organic substances. This study provides key information for achieving sustainable operation of GDM as seawater pretreatment.

2. Materials and methods

2.1. Raw seawater

Raw seawater was collected from the Tuas Spring Desalination plant, Singapore. The pH, conductivity, dissolved oxygen of raw seawater are given in Table 1.

2.2. Experimental setup and operating conditions

2.2.1. GDM filtration cell system

The GDM filtration cell setup was described previously (Akhondi et al., 2015). In summary, the setup was located inside a dark container and all filtration cells, tubings, and tanks were covered by aluminium foil in order to prevent algal growth. Feed seawater was added to the storage tank periodically, and pumped to the feed tank. The water level in the feed tank was kept constant by overflow, which was connected to the storage tank. The feed seawater flowed from the feed tank to membrane filtration cells, which were located 40 cm below the water level of the feed tank (i.e., a hydrostatic pressure of 40 mbar). The permeate of the filtration cell was collected using a plastic bottle and the weight of permeate was measured using an electric balance (OHAUS, USA) on a daily basis. The membrane filtration cell comprised bottom and top parts. The top had a glass window that allowed observation of the biofouling layer morphology. Before the clean membranes were put in the filtration cell, they were soaked in distilled water for 24 h to remove impurities.

The GDM filtration cells were used to investigate the effects of three different flat-sheet membranes and one hollow fibre membrane and different pre-treated seawaters on GDM filtration performance. In the first group of experiments, the four GDM filtration systems were operated with four types of membranes fed with raw seawater. The membrane properties are listed in Table 1. The hollow fibre membranes had an internal diameter of 0.6 mm and external diameter of 1.2 mm. The hollow fibre membranes were horizontally orientated and the operation mode was outside-in. In the second group of experiments, three prefiltration meshes with sizes of 10 μm, 100 μm, and 1000 μm were employed to pretreat the raw seawater. For each prefiltered seawater, two GDM filtration experiments (flat sheet PES membrane, 100 kD, Microdyn-Nadir, Germany) were performed in parallel. All the experiments were performed at room temperature (23 ± 1 °C).

2.2.2. Hybrid biofilm-submerged GDM reactor

The hybrid biofilm-submerged GDM filtration system is illustrated in Fig. 1. Raw seawater in the feed tank was pumped to the biofilm reactor (3.6 L) filled with Kaldnes K3 biofilter media (China). The feed flow rate was regulated according to the permeate flow rate, which ensured a total hydraulic retention time of ~40 h. The effluent from the biofilm reactor was delivered to the GDM tank (8 L) and the effluent from the GDM tank was returned back to the biofilm reactor via a two-channel peristaltic pump (Cole–Parmer, US) at an average recirculation rate of 150 ml/min. The constant effluent level of the GDM tank ensured a hydrostatic pressure of 40 mbar. As a control, a submerged GDM reactor was operated without a biofilter column. Two sandwich type membrane modules (PES, 100 kDa, Microdyn-Nadir, Germany, Figure S1), each with a membrane area of 0.0198 m^2 were submerged in the GDM tank and the respective permeate was collected in a beaker. All the experiments were performed at room temperature (23 ± 1 °C).

2.3. Analytical measurements

The dissolved organic carbon (DOC) of the raw seawater (after