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Effects of shear rate on biofouling of reverse osmosis membrane during tertiary wastewater desalination

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ABSTRACT

The effects of shear rate in operation of reverse osmosis (RO) membrane process on biofouling phenomena were studied. RO filtration unit was continuously fed with tertiary effluents at high (445.2 s^{-1}) and low (178.1 s^{-1}) shear rate conditions. In addition, the two dependent parameters, organic loading rate and shear rate were compared. During desalination process of tertiary effluents, two different stages of fouling were observed. As expected, conditioning the RO membrane during the first stage of fouling was dominated by the concentration of the organic compounds in the feed water. While in contrast, the 2nd stage mainly comprised of biofilm formation, was dominated by the organic loading rate to the RO flowcell. Shear rate is shown to affect extracellular polymeric substances (EPS) chemical composition, which corresponded to changes in EPS cohesion and elasticity. Consequently, we show how these EPS physical properties affect permeate flux decline. At higher shear rate, EPS elasticity increases, probably inducing biofilm compactness and enhancing permeate flux decline with smaller amount of biofilm. EPS is known to induce permeate flux decline by increasing the hydraulic resistance to permeate flux. Here, we elucidate the strong impact of high shear rate biofouling conditions on permeate flux decline by the combination of EPS adhesion and cohesion properties.

1. Introduction

The decrease in reverse osmosis (RO) membrane performance brought by fouling (inorganic, organic and biological) represents a formidable challenge for seawater and tertiary wastewater desalination including a decrease in permeate flux, decrease in salt rejection and increase in frequency of membrane chemical cleaning [1,2]. Dissolved organic matter in treated wastewater effluent, commonly known as effluent organic matter (EfOM), has been found to be mostly made up of soluble microbial products (SMP) [3] and has been associated with significant RO fouling. As with organic fouling, biofouling is particularly prevalent within water reclamation applications. Biofilm formation on membranes impairs their performance in two ways. First, biofilms can produce additional resistance to water flow, which is known to be detrimental in porous membranes such as ultra- and micro-filtration as well as in RO systems, adding hydraulic resistance through the membrane. Second, biofilms prevent effective mixing in the solution immediately adjacent to the surface, which enhances concentration polarization (CP), impacting selectivity and increasing osmotic pressure in UF, NF and RO processes [4]. In fact, CP further facilitates biofouling since the transmembrane flow results in more uniform access to nutrients and oxygen by the biofilm [5]. Membrane fouling is determined by the coupled influence of physical and chemical interactions [6–8]. These interactions and the resulting physical properties of the fouling layer are controlled by the foulant characteristics, feed water solution chemistry (pH, ionic strength, divalent cations concentration), membrane properties (surface charge, hydrophobicity, roughness), and hydrodynamic conditions (permeate flux, crossflow velocity).

Previous studies suggest that biofilm associated membrane damage that includes subsequent cleaning efforts, arises from the presence of an extracellular polymeric substances (EPS) matrix secreted and deposited on the membrane, and not from the microorganisms themselves [9]. EPS are metabolic products, resulting from active secretion from mainly sessile cells. In most cases, polysaccharides and proteins are the major constituents of the EPS matrix [10,11]. The heterogeneous nature of the EPS mixture consists of both aromatic and aliphatic components with three main functional groups: carboxylic acids (COOH), phenolic alcohols (OH), and methoxycarbonyls (C=O) [12]. EPS electric charge, derived mainly from the ionization of these groups, results in mutual repulsion and expansion of the biopolymers.

Two dependent operating conditions in RO installations are organic loading rate and fluid shear rate both are affected by the

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feed water flow velocity to the RO module. These operational parameters were reported to influence significantly the biofouling process [13–15]. Biofilm accumulation is determined by the balance between attachment rate of planktonic cells, biomass growth rate and biofilm detachment rate. Increasing linear fluid velocity could induce the higher loading rate of nutrients to the biofilm and may contribute to faster biofilm growth. On the other hand, higher linear flow velocity also implies larger shear rate and could lead to reduced CP as well as extended biomass detachment. The higher shear conditions may also reduce cell attachment rate up to some degree [16]. It has been proposed that increasing the linear flow velocity may be a suitable method to reduce biofouling in tubular heat exchangers [17], since the shear rate is increased by elevation of the linear flow velocity. In addition to the biomass accumulation, the flow regime influences the biofilm morphology. Vrouwenvelder et al. [16] studied the influence of flow regime on biofilm accumulation and morphology in spiral wound nanofiltration and reverse osmosis membranes. A high shear rate resulted in more compact and less filamentous biofilm structure while a fluffy biofilm was produced at low shear rate. Biofilm formed at low shear rate was easier to remove during water flushing compared to a biofilm formed at high shear. In conclusion, so far, shear rate has been reported to influence biofilm morphology, to affect membrane performance [16,18], and is required to be further studied under desalination and biofouling conditions. Despite extensive biofilm literature, systematic studies on the influence of shear rate on the RO biofouling process are scarce. In this study, the effects of shear rate on organic- and bio-fouling, tested as permeate flux decline and decrease in salt rejection during operation of RO membrane process were investigated. We hypothesized that shear rate alters performance of RO membranes that consequently results in permeate flux decline and decreased salt rejection. These effects are shown to be an outcome of firstly, conditioning the membrane with organic fouling and secondly, by biofilm growth and its EPS composition and adhesion properties.

2. Materials and methods

2.1. Experimental setup

2.1.1. Hybrid growth-MBR (HG-MBR) operation and production of tertiary wastewater effluent

A hollow fiber UF membrane module of ZW-10 (Zenon Inc., Canada) with a nominal pore size of 0.04 μm and a total filtering surface area of 0.93 m^2 was submerged in the center of a 190 L reactor (Fig. 1(A)). AqWise carriers (AqWise, Israel) made from high-density (0.96 g cm^{-3}) polyethylene were supplemented to the MBR as a biofilm support surface area. Detailed information on the HG-MBR setup, operation, and process analysis is reported in our previous publication [19].

2.1.2. RO membrane and crossflow test unit

A commercial thin film composite reverse osmosis membrane, ESPA-1 (Hydranautics, Oceanside, CA), was used as a model membrane for the biofouling experiments. The hydraulic resistance was determined to be 1.53 ($\pm$0.012) $\times 10^{14}$ m^{-1} at 25 °C. The observed salt passage for clean RO ESPA-1 membrane was 3.40 $\pm$ 0.31%, as determined using the tertiary wastewater described above at an applied pressure of 10×10^5 Pa (10 bar) and a crossflow velocity of 8.9 cm s^{-1}. The membrane was received as a flat sheet and stored in DDW at 4 °C. A laboratory scale RO test unit, similar to that described in previous publications [20,21] (Fig. 1(B)), was used for the biofouling experiments. The unit comprised a membrane crossflow cell, high-pressure pump (Hydra-Cell, Wanner Engineering Inc.), feed water reservoir, chiller equipped with a temperature control system (Recircula 6000, PolyScience), and a data acquisition system (PC interfaced), used to acquire the permeate flow rate (Liquid Mass 5891 flowmeter, Brooks, LTD), conductivity (PCD 6500, Eutech), and dissolved oxygen concentration (Pro 20, YSI). Retentate flow rate was monitored with a floating disk rotameter (Floating rotameter, Stübbe). The dimensions of the rectangular, crossflow, channel membrane unit were 7.7 cm $\times$ 2.6 cm with a channel height of 0.3 cm. Both permeate and retentate were recirculated back to the feed reservoir.

2.1.3. Biofouling protocol

A scheme of the completely mixed RO desalination unit for fouling and biofouling growth is presented in Fig. 1(B). Fouling and biofouling experiments were performed in duplicate at a constant transmembrane pressure of 10 bars and initial permeate flux of 40 L m^{-2} h^{-1} under different crossflow velocities associated with different shear rate values. The completely mixed RO laboratory test unit enable us to work with laboratory scale tertiary wastewater supply and constant RO feed water characteristics.

The high and low shear rate values were 445.2 S^{-1} and 178.1 S^{-1}, respectively, according to the calculation of Davis [22]. Increasing the cross flow velocity would elevate both shear

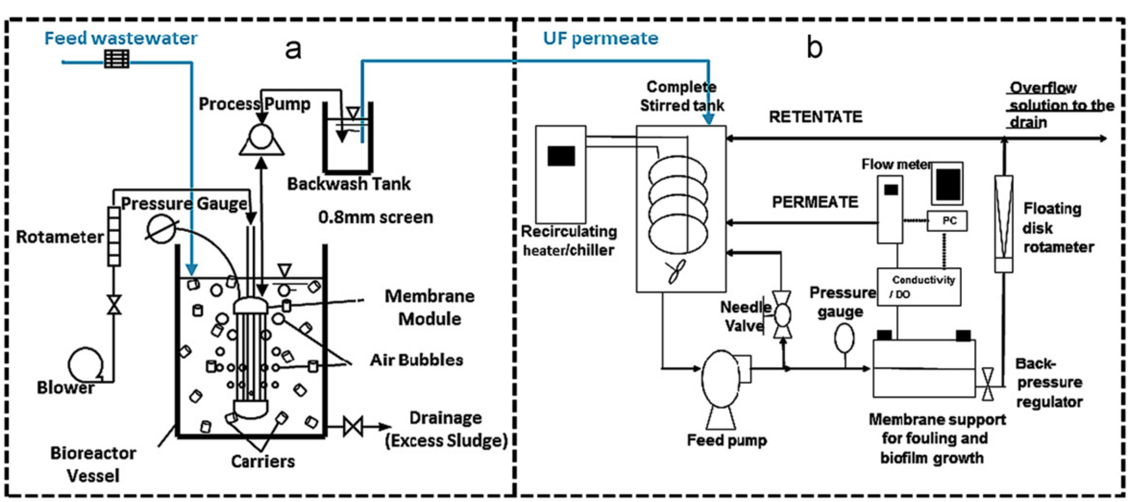

Fig. 1. (A) Hybrid growth MBR; (B) RO desalination unit for fouling and biofouling growth (working volume: 10 L, working temperature: 25 °C), desalinating UF permeate from the HG-MBR.