Desalination 343 (2014) 26–37

Contents lists available at ScienceDirect

Desalination

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

Effect of different commercial feed spacers on biofouling of reverse osmosis membrane systems: A numerical study

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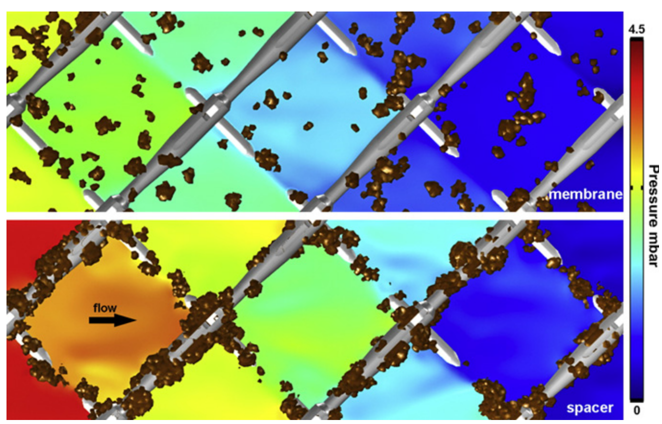
HIGHLIGHTS

- A micro-scale biofouling model describes existing experimental observations well.
- The biofilm developed on the spacer has the highest impact on pressure drop increase.
- The shape of the spacer filaments influences the feed channel pressure drop.
- Thicker spacer use reduces the effect of biofouling on feed channel pressure drop.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 August 2013
Received in revised form 4 October 2013
Accepted 4 November 2013
Available online 23 November 2013

Keywords:
Feed spacer
3-d mechanistic model
Biofouling
Desalination
Drinking water

ABSTRACT

Feed spacers and hydrodynamics have been found relevant for the impact of biofouling on performance in reverse osmosis (RO) and nanofiltration (NF) membrane systems.
The objectives of this study on biofouling development were to determine the impact of (i) linear flow velocity and bacterial cell load, (ii) biomass location and (iii) various feed spacer geometries as applied in practice as well as a modified geometry spacer.
A three-dimensional mathematical model for biofouling of feed spacer channels including hydrodynamics, solute mass transport and biofilm formation was developed in COMSOL Multiphysics and MATLAB software.
Results of this study indicate that the feed channel pressure drop increase caused by biofilm formation can be reduced by using thicker and/or modified feed spacer geometry and/or a lower flow rate in the feed channel. The increase of feed channel pressure drop by biomass accumulation is shown to be strongly influenced by the location of biomass. Results of numerical simulations are in satisfactory agreement with experimental data, indicating that this micro-scale mechanistic model is representative for practice. The developed model can help to understand better the biofouling process of spiral-wound RO and NF membrane systems and to develop strategies to reduce and control biofouling.

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http://dx.doi.org/10.1016/j.desal.2013.11.007

1. Introduction

Membrane filtration processes like reverse osmosis (RO) and nanofiltration (NF) have become increasingly important for high quality drinking water production in recent years. The major problem of this technology is biofouling — excessive growth of biomass leading to reduction of produced water quantity and quality, while increasing the operational costs.

Feed spacers are essential parts of the spiral-wound NF and RO modules that keep membranes apart to form the flow channel and to promote mixing of the fluid. Baker et al. [1] reported that initial deposits of fouling were found to accumulate alongside the membrane feed channel spacer and with time these deposits encroached upon the remaining free membrane area. Van Paassen et al. [2] observed an exponential increase of the feed channel pressure drop caused by biofouling build up onto the feed spacer of the membrane modules. This biofouling proved to be related with chemicals dosed to the feed water. Tran et al. [3] found that the vicinity of the feed spacer strands was most affected by fouling. Strategies to reduce feed spacer biofouling have been addressed, e.g. periodic air/water flushing [4] and applying thick feed spacers [5]. Vrouwenvelder et al. [6] showed that for fresh water the feed spacer biofouling is much more important than membrane biofouling for feed channel pressure drop increase and thus for overall performance decline. In summary, feed spacers are important for membrane performance and play a key role in biofouling of membrane systems. Therefore, a better understating of the impact of feed spacers on biofouling is of primary importance for an improved design of the spiral-wound membrane modules.

According to Li et al. [7], feed spacers can be characterized by four parameters: (i) the distance between spacer filaments, (ii) the angle between spacer filaments, (iii) the flow attack angle and (iv) the total spacer thickness. Sablani et al. [8] studied experimentally the influence of three feed spacers varying in thickness 20, 28 and 46 mil (1 mil = 25.4 μm; i.e., a 28 mil spacer = 711 μm thick) on concentration polarization. They found a decrease in flux with decreasing spacer thickness, but the highest permeate flow was obtained for the intermediate spacer thickness. Recently, Araujo et al. [9] studied experimentally the effect of different spacer thickness on biofouling. Their findings showed that with the increase of spacer thickness there is a decrease of the feed channel pressure drop due to biofouling.

Computational fluid dynamics (CFD) has become a widely used tool in studying the hydrodynamic behaviour of NF and RO membrane systems [10]. Many studies using CFD focused on the effect of feed channel spacer on fluid flow and mass transfer with different type of spacers [11–15]. Simplified, cylindrical shapes were used for representation of spacer filaments in most of the numerical studies on the effect of feed spacer geometry on mass transfer and fluid flow. Stereomicroscopic observations of the feed spacer revealed that the spacers used in commercially available spiral-wound membrane modules have more complicated geometry, with filaments varying in thickness and thinnings [16]. Picioreanu et al. [17] found by numerical simulations that the feed channel pressure drop for a simplified spacer with cylindrical filaments is significantly different from a more realistic spacer geometry with filament thinnings. Although the effect of feed spacer geometry has been extensively studied, it is still not clear how spacers affect biofouling and the performance parameters.

In this study we examined with a numerical model the impact on feed channel pressure drop of: (i) liquid flow velocity and bacterial cell load; (ii) biomass location on the spacer and/or membrane surfaces and (iii) various feed spacer geometries (28, 31, 34 and 46 mil thick) as applied in commercially available spiral-wound reverse osmosis modules and a modified geometry having a 31 mil thick spacer. To the authors knowledge this is the first paper using a three-dimensional mathematical model on biofouling evaluating several realistic geometries (commercially available) feed spacers as used in full-scale spiral-wound membrane modules.

2. Model description

A three-dimensional numerical model was developed to study the impact of feed spacer geometry on the biofouling of feed channels of spiral-wound membrane modules. The model is based on the work of Picioreanu et al. (2009), implemented here in more efficient computer code coupling COMSOL Multiphysics solvers (COMSOL 4.3a, Comsol Inc., Burlington, MA, www.comsol.com) for fluid dynamics and solute transport with MATLAB (MATLAB 2011a, MathWorks, Natick, MA, www.mathworks.com) code for biofilm formation.

2.1. Spacer geometry

Geometries corresponding to four commercially available feed spacers used in full-scale spiral-wound RO modules were characterized using a calibrated stereomicroscope (Leica M205 FA), followed by measurements using Qwin Pro 3.1.0 software, then reconstructed in the COMSOL Multiphysics environment. The studied spacers differ in thickness, porosity and their filament shapes. For each filament, several characteristic dimensions were considered, according to Fig. 1A. Every spacer is constructed from two perpendicular layers of filaments (Fig. 1B), and the filaments from each layer have a unique shape. The spacer filaments differ mainly in their diameter, with several specific regions identified for all filaments determining a characteristic shape, as shown in Fig. 1A. The dimensions and the flow channel porosity for each spacer type are presented in Table 1. Additionally, a hypothetical 31 mil thick modified spacer geometry was created to study the effect on feed channel porosity of spacers having the same thickness but different filament dimensions.

The spacer geometries used in commercially available RO and NF modules have standard thicknesses, but they can be provided by different manufacturers and produced by different technologies, which may lead to diverse spacer geometries. These spacers vary especially with respect to the spacer unit length L_{tot} and the flow channel porosity (Table 1). All studied commercial feed spacers are displayed in Fig. 2.

2.2. Computational domain

The standard size of the industrial spiral-wound RO and NF module is a length of 40 in. (~1 m) and a diameter of 8 in. (~0.2 m) with a total membrane surface area of ~40 m^2. A numerically accurate three-dimensional model of flow and biofilm formation in such a large area is virtually impossible within current computational limits. Still, because of the repetitive unit spacer geometry, the essential flow and biofilm formation patterns can be captured within a smaller scale computational domain. The size of the computational domain used in this study is in the range of 10^{-5} m^2. The exact length, width and height of the computational domain differs with the spacer geometry. In all cases, five spacer units in diamond configuration (i.e., 45° rotated against the main flow direction) were placed in the computational domain (Fig. 1C). This is the current compromise between the necessary calculation time and model realism.

The computational domain consisted of feed channel volume available for flow and resulted from subtracting the spacer volume from a box bounded by membranes, inlet, outlet and lateral surfaces (Fig. 1C). An imprint of the feed channel spacer on the membranes can be observed during autopsies of spiral-wound RO modules, which suggests that the spacer filaments are actually pressing into the membranes on a sizeable contact area. Therefore, the flow channel was constructed so that the two membrane planes cut 5 μm from the spacer top and bottom [11]. In addition to more realistic model geometry, this construction also avoids very sharp angles in contact areas, which usually lead to computational difficulties and many unnecessarily small mesh elements.