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

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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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 understanding 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 increasing 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 types 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]. Picoreanu 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 Picoreanu 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 Lw 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 m². 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 m². 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.

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2.3. Liquid flow, substrate transport and biofilm formation

Processes influencing biofouling may occur at very different time scales. Therefore, while the slow biofilm formation was evaluated in dynamic conditions (i.e., in time), the fast hydrodynamics and soluble substrate transport were considered stationary at each time step during biofilm development. More details regarding the time scale separation in biofilm models can be found in [18].

2.3.1. Liquid flow

It was shown by Fimbres-Weihs and Wiley [10] that the water flow in feed channels with spacers is laminar up to a Reynolds number (Re) of 200 for spacers with 45° orientation of filaments, but becomes unsteady for Re between 200 and 300. Re numbers were computed according to Schock and Miquel [19]. For all geometries Re was less than 200, therefore the Navier–Stokes equations were used to model the laminar, incompressible and stationary flow which was assumed during the whole simulation process:

\[
\rho \left( \mathbf{u} \cdot \nabla \mathbf{u} \right) + \nabla p = \nabla \cdot (\eta \nabla \mathbf{u}), \quad \nabla \cdot \mathbf{u} = 0
\]

with \( \mathbf{u} = (u_x, u_y, u_z) \) the flow velocity vector, \( p \) the pressure, \( \rho \) the density and \( \eta \) the dynamic viscosity of water. The boundary conditions were set according to Fig. 1C. Fully developed laminar flow was assumed at the inlet \( x = 0 \), with the average fluid velocity \( u_{in} \). On the outlet boundary at \( x = L_x \) zero pressure (arbitrarily chosen as reference value) and no viscous stress conditions were imposed. The top and bottom membrane surfaces (\( z = 0 \) and \( z = L_z \)), as well as the whole spacer surface were no-slip walls (\( u = 0 \)). On the lateral boundaries (\( y = 0 \) and \( y = L_y \)) periodic conditions were applied, as frequently used in simulations for geometries with a repeating pattern [13].

2.3.2. Substrate transport and reaction

Biomass grows in spiral-wound membrane modules as function of local concentrations of biodegradable substrates. The concentration field, \( C_S \), of a single soluble substrate assumed here limiting for biomass growth was calculated from a convection–diffusion–reaction equation:

\[
D_S \nabla^2 C_S - \mathbf{u} \nabla C_S + r_S = 0
\]

with diffusion coefficient of substrate \( D_S \). The substrate is transported by convection and diffusion in the bulk liquid and only by diffusion in the

<p>| Table 1 |
| Dimensions of different types of feed spacers used in this study, according to Fig. 1. For each spacer type, the filament dimensions (in ( \mu m )) for the two layers of filaments are presented in columns: (A) thinner filament and (B) thicker filament. |</p>
<table>
<thead>
<tr>
<th>Spacer thickness (mil)</th>
<th>28 mil</th>
<th>31 mil</th>
<th>31 mil modified</th>
<th>34 mil</th>
<th>46 mil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Dimensions (( \mu m ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>862</td>
<td>877</td>
<td>983</td>
<td>299</td>
<td>400</td>
</tr>
<tr>
<td>L2</td>
<td>595</td>
<td>740</td>
<td>557</td>
<td>132</td>
<td>100</td>
</tr>
<tr>
<td>L3</td>
<td>767</td>
<td>595</td>
<td>358</td>
<td>417</td>
<td>1780</td>
</tr>
<tr>
<td>L4</td>
<td>178</td>
<td>252</td>
<td>340</td>
<td>1036</td>
<td>100</td>
</tr>
<tr>
<td>L5</td>
<td>386</td>
<td>324</td>
<td>542</td>
<td>896</td>
<td>400</td>
</tr>
<tr>
<td>D1</td>
<td>354</td>
<td>449</td>
<td>447</td>
<td>446</td>
<td>446</td>
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<tr>
<td>D2</td>
<td>221</td>
<td>289</td>
<td>263</td>
<td>272</td>
<td>263</td>
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<tr>
<td>L_{tot}</td>
<td>2788</td>
<td>2788</td>
<td>2780</td>
<td>2780</td>
<td>2780</td>
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<tr>
<td>D_{tot}</td>
<td>711</td>
<td>787</td>
<td>863</td>
<td>787</td>
<td>863</td>
</tr>
<tr>
<td>Channel porosity</td>
<td>0.90</td>
<td>0.89</td>
<td>0.92</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

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biofilm. The specific growth rate of the microorganisms ($\mu$) was computed according to the simple Monod kinetics:

$$\mu = \mu_{\text{m}} \frac{C_S}{K_S + C_S}$$  \hspace{1cm} (3)

where $\mu_m$ is the maximum specific growth rate of the microorganisms, $K_S$ is the Monod half-saturation coefficient and $C_S$ is the local biodegradable substrate concentration in the biofilm. Monod-type microbial growth rates are commonly applied for biofilm growth [20–22]. The biomass growth rate $r_X$ was linear with respect to $C_X$ (biomass concentration in the biofilm):

$$r_X = \mu \cdot C_X$$  \hspace{1cm} (4)

The substrate consumption rate by biomass, $r_S$, was calculated neglecting the maintenance:

$$r_S = Y_S \cdot r_X$$  \hspace{1cm} (5)

where $Y_S$ is the yield coefficient (mol substrate consumed per C-mol biomass formed). A constant inlet concentration $C_{S,in}$ was assumed at $x = 0$, while the outlet ($x = L_x$) was a zero-diffusion boundary. Periodic conditions were set for the lateral boundaries at $y = 0$ and $y = L_y$. The membranes and spacer surfaces were set as impermeable walls.

2.3.3. Biofilm formation

The biofilm development in the feed channel was governed in this model by two processes, microbial attachment and growth. Biomass detachment also plays a role in biofilm development, but mainly at late stages of biofouling development (i.e., thick biofilms). Effects of biofilm detachment on biofouling will therefore be addressed in follow-up studies. Biomass was allowed to attach to randomly chosen places in the computational domain. Three different attachment modes were studied: (i) only on the spacer surface, (ii) only on the membrane surface and (iii) on both spacer and membrane surfaces. The cellular automata (CA) biofilm model developed in [23,24] and modified as in [17] was used to simulate the biofilm growth in a spiral-wound membrane system. The biomass growth is calculated in each volume element by a Monod equation linked to the substrate consumption rate:

$$\frac{dC_X}{dt} = r_X$$  \hspace{1cm} (6)

In every volume element of a 3-d grid a maximum biomass concentration was set to $C_{\text{max}}$. Once the maximum biomass concentration for a grid element is exceeded, the biomass amount is divided in two parts. One part will remain in place, while the second part will be re-positioned in space according to the CA algorithm as explained in [23,24].

2.4. Model solution

The model solution algorithm follows the procedure described in detail in [17]. After the model geometry was created, the biofilm development was followed iteratively in discrete time steps of size $\Delta t = 4$ h. The liquid flow and substrate distributions reach their steady state fast enough (~seconds) compared to the chosen $\Delta t$ (~hours) to be considered stationary for each time interval of biofilm development. After updating the biomass distribution in one time step, Eqs. (1) and (2) are used again, for calculating the new stationary flow and concentration fields. For the calculations of liquid flow and mass transport of the soluble substrate a tetrahedral mesh was built with maximum element size of 90 $\mu$m. This resulted for 31 mil thick feed spacer geometries in a total of more than 1,300,000 mesh elements. The calculated substrate concentration field was then used in the biomass growth, followed by biomass spreading and attachment of new biomass. The main algorithm was implemented in a MATLAB script split into several steps:

A. define model parameters (Table 2), create the model geometry, computational domain and build equations in COMSOL (Fig. 3A)
B. create the finite element mesh for flow and mass transport calculations in COMSOL (Fig. 3B)
C. solve the laminar flow Eq. (1) in COMSOL for the flow velocity $\mathbf{u}$ and pressure $p$ (Fig. 3C)
D. solve substrate transport-reaction Eq. (2) for concentration $C_S$ (Fig. 3D)
E. evaluate biomass growth from Eq. (6) to get a new $C_B$; transport biomass by the CA method; attach new biomass (Fig. 3E). After this biomass update the time is incremented with $\Delta t$ and the algorithm flow returns to step C.

3. Results

The model was used to investigate the effect of linear flow velocity, bacterial cell load, biomass attachment location, and different commercially available and modified feed spacer geometries on biofouling and feed channel pressure drop evolution. All simulated cases are listed in Table 3.

3.1. Effect of linear flow velocity

The linear flow velocity varies along the length of a membrane filtration installation, consisting of several membrane elements installed in series. Also, a variation of linear flow velocities has been reported in the lead membrane elements in practice, from 0.07 to about 0.2 m·s$^{-1}$ [25].

Numerical simulations were run with different linear flow velocities and compared with experimental data (feed channel pressure drop, pressure drop increase) obtained in similar conditions by Vrouwenvelder et al. [22] in experimental studies with membrane fouling simulators (MFS). For this set of simulations the 31 mil (787 μm) thick feed spacer geometry was used at different linear flow velocities of $u_{in} = 0.163$ m·s$^{-1}$ (corresponding to hydrodynamic conditions frequently encountered in industry), 0.082 m·s$^{-1}$ and 0.041 m·s$^{-1}$, the other model parameters being set as listed in Tables 2 and 3.

The initial pressure drop in absence of fouling (Fig. 4A, day 0) showed a small difference (~10%) between the simulation and experimental initial pressure drop. This difference may be due to e.g. the variations in thickness and geometry of the spacer used in the experiments, but also to assumptions in the model calculations.

In time, the development of pressure drop caused by biofilm accumulation resulted in a similar trend for both model simulations and experimental studies. Small dissimilarities between the calculated and measured data are observed. The amount of accumulated biomass was the same at the end of the simulation studies (day 6), since the same biomass attachment rate was used for all simulations and no detachment was considered. With increasing linear flow velocity the effect of the accumulated fouling material (biomass) on pressure drop increased (Fig. 4B). These results show that by applying a lower linear velocity the impact of the fouling material on performance can be significantly reduced. In summary, the biofouling model describes existing experimental observations for pressure drop and pressure drop increase well. However, in reality the linear velocity has more complex implications in terms of substrate load, bacterial transport and deposition rates, as well as biomass detachment rates. All of these factors impact the amount of accumulated biomass and, consequently, the feed channel pressure drop.

3.2. Effect of bacterial cell load

The biofouling onset may also be affected by the bacterial cell load (i.e., cell concentration multiplied by linear flow velocity) in the feed channel. It is expected that when increasing the liquid flow rate, more microorganisms would pass through the channel per unit time [26], therefore more cell attachment could take place due to the higher cell supply and higher shear rate. Eventually, a maximum deposition rate exists function of wall shear rate [27]. Because the decreased deposition efficiency at high shear rates relates to detachment rates, not included in our model, this effect has to be systematically checked in future studies. For investigating the effect of cell load on performance decline, the 31 mil (787 μm) thick feed spacer was used in numerical simulations at different flow and cell attachment rates (Table 3). Three cases were studied when the transported amount of biomass varied with flow rate: the cell attachment rate was reduced proportionally with the reduction in flow rate. Comparing the results obtained at different linear flow velocities and constant attachment rate (see Table 3, effect

---

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum biomass concentration in a grid element</td>
<td>$C_{B,max}$</td>
<td>1400</td>
<td>mol·m$^{-3}$</td>
<td>[14]</td>
</tr>
<tr>
<td>Biomass maximum specific growth rate</td>
<td>$\mu_B$</td>
<td>$1.25 \times 10^{-5}$</td>
<td>s$^{-1}$</td>
<td>Chosen</td>
</tr>
<tr>
<td>Substrate half-saturation coefficient</td>
<td>$K_s$</td>
<td>0.05</td>
<td>mol·m$^{-3}$</td>
<td>Chosen</td>
</tr>
<tr>
<td>Substrate concentration in the inlet</td>
<td>$C_{S,in}$</td>
<td>0.4</td>
<td>mol·m$^{-3}$</td>
<td>Chosen</td>
</tr>
<tr>
<td>Yield of substrate consumed per C-mol biomass</td>
<td>$Y_S$</td>
<td>1</td>
<td>mol·(Cmol)$^{-1}$</td>
<td>Corresponding to acetate</td>
</tr>
<tr>
<td>Diffusion coefficient of substrate</td>
<td>$D_S$</td>
<td>$1 \times 10^{-9}$</td>
<td>m$^2$·s$^{-1}$</td>
<td>Small solute in water</td>
</tr>
<tr>
<td>Liquid density</td>
<td>$\rho$</td>
<td>1000</td>
<td>kg·m$^{-3}$</td>
<td>Water</td>
</tr>
<tr>
<td>Liquid viscosity</td>
<td>$\eta$</td>
<td>0.001</td>
<td>Pa·s</td>
<td>Water</td>
</tr>
</tbody>
</table>

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Fig. 3. Graphical representation of the model algorithm. The arrows indicate the sequence of algorithm steps, with a loop between steps (C) and (E). (A) sets model parameters and geometry in MATLAB and COMSOL; (B) creates the 3-d tetrahedral mesh and 3-d rectangular biomass grid; (C) calculates fluid flow (blue arrows: local flow velocity in a slice at half the flow channel height); (D) calculates substrate concentration (colour scale: solute distribution in a slice at half the flow channel height; blue: minimum; red: maximum); and (E) biomass attachment and growth (brown volume: biomass). In all the top-view figures of the 3-d model system the spacer filaments are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
of linear velocity; i.e., constant cell load) with those at flow-linked attachment rate (see Table 3, effect of cell load: i.e., variable cell load) reveals that at lower linear fluid velocities the impact of accumulated biomass is lower. Possibly because of differences in hydrodynamics and less biomass attachment in the biomass is lower. Possibly because of differences in hydrodynamics of linear velocity: i.e., constant cell load) with those at Variable model parameters in different simulations.

Table 3

<table>
<thead>
<tr>
<th>Variable model parameters in different simulations.</th>
<th>Spacer thickness [mil]</th>
<th>[μm]</th>
<th>$r_a^*$ [Cmol·m$^{-2}$·h$^{-1}$]</th>
<th>$u_w^*$ [m·s$^{-1}$]</th>
<th>Q$^*$ [L·h$^{-1}$]</th>
<th>Attachment location</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of linear flow velocity</td>
<td>31</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.1</td>
</tr>
<tr>
<td>Effect of linear flow velocity</td>
<td>31</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.2</td>
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<tr>
<td>Effect of linear flow velocity</td>
<td>31</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane spacer</td>
<td>3.3</td>
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<tr>
<td>Effect of linear flow velocity</td>
<td>31</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane spacer</td>
<td>3.4.1</td>
</tr>
<tr>
<td>Effect of linear flow velocity</td>
<td>31 modified</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
</tr>
<tr>
<td>Effect of linear flow velocity</td>
<td>31 modified</td>
<td>711</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.178</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
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<tr>
<td>Effect of linear flow velocity</td>
<td>31 modified</td>
<td>787</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
</tr>
<tr>
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<td>863</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.153</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
</tr>
<tr>
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<td>1168</td>
<td>$1.08 \times 10^{-2}$</td>
<td>0.115</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
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<tr>
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<td>31 modified</td>
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<td>$1.08 \times 10^{-2}$</td>
<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
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<tr>
<td>Effect of linear flow velocity</td>
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<td>0.163</td>
<td>16.0</td>
<td>Membrane + spacer</td>
<td>3.4.2</td>
</tr>
</tbody>
</table>

$^a$ Biomass attachment rate.
$^b$ Average flow velocity in inlet.
$^c$ Liquid volumetric flow rate (as experiments from [9]).
studies the effect of four different commercially available and one hypothetical feed spacer geometry on the feed channel pressure drop and pressure drop increase due to accumulation of biomass. The spacer geometries used in the industrial modules which are subject of this study differ in their thickness and filaments shape. The simulation conditions, such as biomass attachment rate, substrate inlet concentration and fluid linear flow velocity, were kept constant in all the cases.

3.4.1. Spacer shape and channel porosity

The modified spacer geometry does not represent an ideal feed spacer geometry, but rather a simple hypothetical construct used to investigate the effect of a different filament shape with the same thickness on performance decline. The numerical simulations clearly show how the feed spacer resistance to flow can be reduced by increasing channel porosity. Small changes in channel porosity (from 89\% for commercial spacer to 92\% for the modified spacer) led to significantly lower initial pressure drop (\sim 20\% lower) and less pressure drop increase in time in the presence of the same amount of biomass (Fig. 9). The feed channel spacer has a narrow area of contact with membrane

Fig. 4. Calculated and experimentally determined data at different linear flow velocities, for the 31 mil (787 \(\mu\)m) thick feed spacer. (A) Pressure drop in time during the biofouling process (lines – calculated data, symbols – measured data); (B) pressure drop increase at day 6 relative to the initial pressure drop.

Fig. 5. Comparing the impact of linear fluid velocity and cell load on feed channel pressure drop. (A) Pressure drop in time (connected line – varying cell load, dashed line for continuous cell load), (B) pressure drop increase due to biomass accumulation (day 6), and (C) accumulated biomass concentration at different linear flow velocities (day 6).

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sheets at the cross section of the filaments. The same thickness at the filament crossings and reduced filament thickness elsewhere, result in a higher feed channel spacer porosity and consequently in a lower pressure drop increase. These results suggest that the spacer thickness (giving channel height), spacer mesh size (distance between filament cross-sections) and the fluid flow attack angle, the filament shape (especially its thickness and thickness variation) is also important for feed channel pressure drop and the impact of biomass on pressure drop increase.

3.4.2. Spacer thickness

Industrial RO and NF membrane modules are available with feed spacers differing in thickness. We studied the effect on feed channel pressure drop of four different geometries corresponding to feed spacers used in commercially available spiral-wound RO/NF modules. The studied spacers displayed in Fig. 2 differed in thickness (28, 31, 34 and 46 mil), porosity and filament shape, and their spatial dimensions are listed in Table 1. Two sets of simulations were run: (i) with constant flow rate, 16 L·h⁻¹ (i.e., different linear flow velocities for different spacer thickness) and (ii) constant linear flow velocity 0.163 m·s⁻¹ (corresponding to various flow rates).

In case of constant flow rate the linear liquid velocity becomes a function of the spacer thickness, with the highest fluid velocity achieved for the narrower 28 mil (711 µm) spacer geometry. As expected, the highest initial pressure drop was found for the thinnest spacer geometry. Both initial pressure drop and pressure drop increase due to biofilm formation show a decreasing trend with increasing feed spacer thickness, as shown in Fig. 10A,B. The initial pressure drop is caused only by the presence of feed spacer, while the pressure drop increase is due to biomass accumulation. Because the amount of accumulated biomass was similar for each type of spacer (7.1 × 10⁻³ Cmol·m⁻² after 6 days), due to identical attachment rate and substrate concentration in all cases (with neglecting biomass detachment, which could have also played a role), it was found that the feed channel pressure drop increase is less affected by biofouling when using thicker spacer.

In the second scenario, a constant linear flow velocity was applied at 0.163 m·s⁻¹. This resulted in varying flow rates because of different channel thicknesses. Similar trend as for the simulations at constant flow rate were observed. Highest pressure drop was found with the thinnest (28 mil) and the lowest with the thickest (46 mil) feed spacer (Fig. 10C,D). However, the initial pressure drop is lower for the case where constant linear flow velocity was applied than for the case with constant flow rate. The difference in pressure drop increase for different spacer thicknesses is similar for the two scenarios, but the change between the different thick spacer geometries is smaller for the second scenario. Results for both cases (constant linear flow velocity and constant flow rate) are in good agreement with the experimental data reported in [9].

4. Discussion

The objectives of the numerical studies on biofouling development in spiral-wound NF and RO systems were to determine the influence of (i) liquid flow velocity and cell load, (ii) biomass location on the feed spacer and membrane surfaces, and (iii) various feed spacer geometries (28, 31, 34 and 46 mil thick) as applied in practice as well as a modified geometry 31 mil feed spacer. The computer simulations were in agreement with existing experimental data on the effect of liquid flow velocity (Fig. 4) on feed channel pressure drop and pressure drop increase caused by biofilm formation, indicating that the model describes experimental data well. Biomass attachment on the feed spacer had the highest impact on pressure drop increase compared to attachment to the membrane only and both the membrane and spacer (Figs. 6–8). Comparison of an in practice applied 31 mil feed...
Spacer with a modified 31 mil spacer geometry showed that the shape of spacer filaments influences the pressure drop and the pressure drop increase caused by biofilm accumulation (Fig. 9). A thicker feed spacer resulted in: reduced initial pressure drop and decreased effect of accumulated biomass on pressure drop increase (Fig. 10).

4.1. Numerical model evaluation

The numerical biofouling model describes existing experimental observations well. Compared to earlier numerical biofouling models, a more detailed geometry for the feed spacer was used (Figs. 1 and 2).

Fig. 8. Effect of biomass attachment location on the development of feed channel pressure drop due to biofilm formation. (A) Pressure drop development in time; (B) pressure drop increase relative to the clean channel (day 6); (C) accumulated biomass in the feed channel. The biomass attachment was randomly allowed (i) only on the feed spacer filaments (red line), (ii) both on the membrane and spacer surface (blue line), and (iii) only on membrane (yellow line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Pressure drop for two feed spacer geometries with the same thickness and same accumulated biomass amount, but differing in channel porosity. (A) Pressure drop in time; (B) pressure drop increase with biomass relative to the clean channel (day 6). Simulations were performed with a 31 mil thick feed spacer as applied in commercially available spiral-wound modules (connected line) and a 31 mil spacer modified for thinner fibres (dashed line).
Also, the numerical model developed by Picioreanu et al. [17] has been implemented successfully in a 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.

Possible future implementations into the model can be biodegradable substrate limitation and biomass detachment. The amount of accumulated biomass in an NF and RO membrane module mostly depends on the available biodegradable substrate concentration and hydrodynamics [25]. Although formally taken into account, the substrate limitation was not very effective due to the chosen combination of C3 and Ks and, as a result, the biomass grew unlimited. If the biomass growth was substrate-limited, then in certain conditions the permeate flux may also have an effect on the biomass growth rate by providing more substrate near the membrane [38]. Biofilm detachment was absent in the model. The biofilm was allowed to develop inside the computational domain without taking in consideration the shearing effect of hydrodynamics. These aspects will be taken into account in the future model versions. How significantly these model limitations affect the main conclusions reached in this study remains to be evaluated in future investigations. However, the match between model results and experiments from Araujo et al. [9] suggests that the model already accounted for the main processes affecting the biofouling process.

### 4.2. Importance of feed spacer for biofouling

One of the factors with strong impact on the operational costs of spiral-wound RO and NF membrane water desalination plants is the pressure drop increase along the modules. The feed channel pressure drop is a result of frictional forces when the fluid flows through the module. The initial pressure drop in an RO module when the feed channel is clean (i.e., no fouling material has accumulated on membranes or spacer) is mainly the result of the feed spacer resistance, which depends on the spacer geometry. It was suggested that by decreasing the linear flow velocity the initial pressure drop can be reduced [32]. However,

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**Fig. 10.** Changes in feed channel pressure drop for different feed spacer thicknesses and geometries (28, 31, 34 and 46 mil thick feed spacers) as applied in commercially available membrane modules. (A,C) Pressure drop in time, (B,D) pressure drop increase relative to the clean channel (day 0). Results at: (A,B) constant flow rate (16 L·h⁻¹); (C,D) constant linear flow velocity (0.163 m s⁻¹).

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by reducing the liquid flow velocity the residence time of the solute increases, which can raise the risk for salt precipitation.

The proposed numerical model indicates that with increasing spacer thickness the effect of biofouling on feed channel pressure drop is decreasing. It was found that with reduced flow rate the amount of accumulated biomass may be lower, which is supported by the experimental findings of Vrouwenvelder et al. [25]. However, Ahmad et al. [39] showed in experimental studies that lowering the feed flow velocity results in an increase of concentration polarization. They also studied the effect of different feed spacer geometries on pressure drop and minimization of concentration polarization, recommending cylindrical spacer filaments at higher fluid velocities, but suggesting alternative spacer filaments at lower flow velocities. Mo and Ng [40] have demonstrated experimentally the importance of feed spacers in reducing the effect of concentration-polarization and fouling but also showed that the presence of the feed spacer creates additional resistance on the permeate flux due to the reduction in effective membrane surface area. Therefore, optimizing a spacer for minimal biofouling in practice needs to account also for the complex interactions between fluid dynamics and mass transport. In other words, a spacer and operating conditions that promote less biomass growth and thus less feed channel pressure drop may adversely affect other performance indicators.

Spiral-wound membrane elements can be produced with thicker feed spacers while maintaining the same membrane surface area [41], indicating that using thicker feed spacers should not significantly increase the investment costs for a membrane plant. Results of Bartels et al. [41] clearly showed that a thicker feed spacer had a lower initial feed channel pressure drop and, more importantly, a lower feed channel pressure drop increase than a thinner feed spacer. For example, in a membrane module a newly designed 34 mil feed spacer had a 16% lower pressure drop than the standard feed spacer of the same thickness. As a result, energy can be saved by using these modules and channel plugging due to biofouling will not rapidly occur. Moreover, the modules with thicker spacer may be more easily cleaned [9,41,42]. In full-scale installations, long term studies were performed with thicker feed spacers at a significantly lower linear flow velocity [41,43] showing that the lower linear flow velocities can be applied in practice without operational problems related to scaling due to higher concentration polarization. In addition, less biofouling was observed, needing thus a lower cleaning frequency. After cleaning, performances close to the initial values were achieved.

The development of effective biofouling control strategies in spiral-wound NF and RO systems most-likely requires detailed insight in the fouling processes obtained under representative conditions, which can be provided by a tuned combination of numerical modelling with experimental studies. Studies on biofouling control without biocides could include the balancing of feed spacer design, hydrodynamics and concentration polarization.

5. Conclusions

The model results emphasise the key importance of feed spacers on the biomass accumulation and performance of NF and RO membrane modules. Numerical simulations indicated that (i) at lower linear flow velocities, the pressure drop increase could be less pronounced because less biomass could accumulate, (ii) biomass on the spacer filaments leads to a higher feed channel pressure drop increase than when developing on the membranes, (iii) the relative feed channel pressure drop increase due to biomass accumulation is much higher at smaller channel porosities and (iv) at same feed flow rate thicker spacers promote a lower pressure drop increase when overgrown with biomass.

Once the model is extended with biomass detachment, flow-influenced biomass attachment and with permeation, this mechanistic approach could help to better predict the biofouling process of RO and NF membrane systems and, eventually, to develop and evaluate novel strategies and optimized spacer geometries to reduce and control biofouling.

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