Three-dimensional modeling of biofouling and fluid dynamics in feed spacer channels of membrane devices

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A B S T R A C T
This study presents a new three-dimensional (3-d) computational model that couples fluid dynamics, solutes transport and biofouling by biofilm formation in NF and RO membrane modules. A computational domain of 3 × 5 feed spacer frames with geometry as applied in practice was used in the model. Comparing the hydrodynamics computed with the realistic spacer geometry and with a spacer made from straight cylindrical filaments, like in previous modeling studies, showed that cylindrical filament feed spacers are too simplified for representative modeling studies. The 3-d numerical simulations showed that biomass accumulation, by attachment and biofilm growth in time, strongly affected the feed channel pressure drop, liquid velocity distribution and residence time distribution. The main pressure drop is encountered by the flow passing over the spacer filaments. Simulations showed the development of a heterogeneous flow pattern and formation of preferential flow channels. This study indicates that the real impact of biofouling is on the flow regime leading to quasi-stagnant zones and an increase in the dispersion of the residence time distribution. The presented 3-d mathematical modeling approach in (bio)fouling of membrane modules may have significant implications for membrane system design and operation to have stable membrane installation performance at minimal costs.

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1. Introduction

Membrane filtration processes like reverse osmosis (RO) and nanofiltration (NF) produce high quality drinking water, virtually free of pathogenic micro-organisms and (in)organic pollutants [1,2]. A major problem in RO and NF applications is membrane fouling, resulting in a pressure drop increase, increasing the plant operation cost. Four major fouling mechanisms of RO and NF membranes can be discriminated: scaling, particulate and organic fouling and biofouling. Scaling by inorganic compounds is usually controlled using a scale inhibitor or an acid. Particulate fouling is controlled by extensive pre-treatment (like ultrafiltration) removing the particulate matter. Thus, all types of fouling except biofouling and organic fouling – related types of fouling – are controllable. Biofouling is in practice the major fouling type in RO and NF membranes fed with extensively pre-treated water. Biofouling is caused by growth of biomass, i.e., biofilms in membrane modules [2–4].

Insight in the factors influencing the development of biomass and pressure drop increase is needed to develop membrane systems less susceptible to biofouling. The relation between fouling accumulation and reduced membrane performance is complex. The linear flow velocity in membrane modules influences the substrate load, the substrate transport and spatial concentration distribution, biofilm growth, biofilm morphology and the effect of accumulated biofilm on the feed channel pressure drop increase [5]. Biofilm accumulation can cause flow channel formation, reducing the water production flux [5]. The effect of biofilms and particulate fouling on salt rejection (and on other solutes that can serve as nutrients to the biofilm), on concentration polarization and on the enhanced osmotic pressure are also important [6–8]. Furthermore, the concentration polarization may affect the biofilm cells physiology and viability by inducing higher substrate levels near the RO membrane [8]. To unravel the influence of individual parameters on membrane performance a three-dimensional mechanistic mathematical model is needed. Major achievements have been made on modeling the effect of spacer on mass transfer and fluid flow. However, fouling is a practical problem and a model coupling hydrodynamics and fouling is still lacking.

There are several important reasons to make this study necessary. First, although computational fluid dynamics models in membrane systems are becoming abundant in the literature (e.g., 3-d models [9–21] and 2-d models [22–36]), none of these includes...
the biofilm growth in the feed channel with spacer separating the two membranes. Consequently, most of the obtained results cannot be applied to biofouling studies, and cannot be directly compared with experimental biofouling data.

Second, fully three-dimensional (3-d) models for flow and mass transfer coupled with biofilm growth are needed. Two-dimensional (2-d) models frequently reported in the literature [22–36] are too simplified to actually represent in a correct way the hydrodynamics in a complicated geometry. 2-d models usually considered equally spaced filaments with cylindrical, triangular or square section (in a cavity, zigzag or submerged configuration [22,23,26–34]), but also other filament structures have been studied [22,24,25]. The potential impact of axially orientated filaments parallel to the flow direction was not considered in 2-d numerical models. In other words, 3-d simulations are essential for a correct description of hydrodynamics. Until now, also the 3-d CFD studies have considered simplified spacer geometries, usually with one layer of straight cylindrical filaments crossed at an certain angle over another layer of straight cylindrical filaments ([9,11,13–18,20,21], see Fig. 1C—the idealized “diamond” geometry). The commercially available spacers are in reality more complex, with filaments of variable cross-section area and with an overlapping area at the filament crossings ([37] and Fig. 1A, B). For this reason, we investigated in this study the extent that these geometry simplifications may have on the obtained flow patterns and on the biofouling development.

Third, most of the studies consider only a very small representative volume [10,11,13,15–18,20]. Usually, the size of such a computational domain is limited to one square formed by four crossing cylindrical spacer filaments. A few studies report simulations on larger domains ([9,12,19,21]), for example with systems of approximately 3 by 5 square elements [9]. Without biomass growth their results show, as expected, a repetitive pattern in each square element once the flow is well established. Due to biofilm growth the flow will get disturbed in a heterogeneous manner, making it necessary to use larger computational domains.

A model including biofilm growth presents an increased computational difficulty compared with the traditional CFD in membrane devices. The modeling approach presented in this paper is based on previous work related with biofilm development in flow conditions, under mass transfer limitation and in complex geometries. The influence of flow on mass transfer and irregular biofilm surface formation on different support geometries has been studied with 2-d models (e.g., [38,39]) and in 3-d [40]. Kapellos et al. in [41] developed an original 2-d simulator for biofilm development in granular porous materials, followed by the work of Graf von der Schulenburg et al. in three dimensions [42]. One important characteristic of biofouling systems is that while the spacer geometry is fixed, the biofilm colonies will grow in time and the boundaries of the channel in which the water flows are continuously changing. We are dealing now with a problem with moving boundary. For this, new computational approaches had to be developed in this work so that the effect of the channel obstruction with biofilms on the flow pattern could be described with sufficient accuracy both over time and in space, while still being numerically efficient.

2. Model description

2.1. Model geometry and computational domains

We present here a three-dimensional model describing the liquid flow, the mass transport of a soluble substrate and the biofilm development in the feed channel of spiral-wound nanofiltration and reverse osmosis membrane devices. The complex geometry of the feed spacer creates an intricate flow pattern, further complicated by the non-uniform biofilm growth in the feed channel. Consequently, the geometry of the domain where the liquid is allowed to flow changes in time as the biofilm develops in the membrane module.

We mainly investigated in this study the spacer geometries as used in real applications. A photograph of one square ele-

![Fig. 1. The modeled and real geometries of the feed spacer. (A) Microscopy image of a square spacer element (diamond configuration). (B) The realistic model spacer element, with geometrical dimensions. (C) The idealized model spacer element, with geometrical dimensions. Dimensions in (B) and (C) are in μm. (D) The computational domain: membranes on the top and bottom sides (z = 0 and 780 μm), lateral periodic boundaries (y = 0 and 12.09 mm), liquid inlet (x = 0) and liquid outlet (x = 20.1 mm). (E) Detail with the finite element mesh used (only the boundary elements are shown).]