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Predicting the impact of feed spacer modification on biofouling by hydraulic characterization and biofouling studies in membrane fouling simulators

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ABSTRACT

Feed spacers are an essential part of spiral-wound reverse osmosis (RO) and nanofiltration (NF) membrane modules. Geometric modification of feed spacers is a potential option to reduce the impact of biofouling on the performance of membrane systems. The objective of this study was to evaluate the biofouling potential of two commercially available reference feed spacers and four modified feed spacers. The spacers were compared on hydraulic characterization and in biofouling studies with membrane fouling simulators (MFSs). The virgin feed spacer was characterized hydraulically by their resistance, measured in terms of feed channel pressure drop, performed by operating MFSs at varying feed water flow rates. Short-term (9 days) biofouling studies were carried out with nutrient dosage to the MFS feed water to accelerate the biofouling rate. Long-term (96 days) biofouling studies were done without nutrient dosage to the MFS feed water. Feed channel pressure drop was monitored and accumulation of active biomass was quantified by adenosine tri phosphate (ATP) determination. The six feed spacers were ranked on pressure drop (hydraulic characterization) and on biofouling impact (biofouling studies). Significantly different trends in hydraulic resistance and biofouling impact for the six feed spacers were observed. The same ranking for *biofouling impact* on the feed spacers was found for the (i) short-term biofouling study with nutrient dosage and the (ii) long-term biofouling study without nutrient dosage. The ranking for *hydraulic resistance* for six virgin feed spacers differed significantly from the ranking of the biofouling impact, indicating that hydraulic resistance of clean feed spacers does not predict the hydraulic resistance of biofouled feed spacers. Better geometric design of feed spacers can be a suitable approach to minimize impact of biofouling in spiral wound membrane systems.

1. Introduction

Clean water scarcity is one of the major global challenges affecting more than 1.2 billion people (United Nations Department of Economic and Social Affairs, 2012). By 2025, two-thirds of the world's population may not have access to clean drinking water (FAO Water Unit Water News: water scarcity, 2015). This necessitates the development and application of better techniques for clean water production by seawater desalination and wastewater reuse. In recent years, due to improved cost effectiveness, water desalination using reverse osmosis (RO) and nanofiltration (NF) is

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increasingly applied globally (Elimelech and Phillip, 2011). RO and NF processes come with operational challenges, leading to performance decline and increased cost.

Fouling of membrane modules is the major cause of performance decline in membrane based water filtration systems. Based on its nature, fouling can be classified into four types namely particulate, inorganic, organic, and biofouling (Flemming, 2002). While other types of fouling can be controlled by pre-treatment, biofouling still occurs due to the presence of small amounts of biodegradable nutrients and micro-organisms in the feed water (Flemming, 2011). Biofouling refers to the undesirable accumulation of biomass on a surface (Characklis and Marshall, 1990) causing an increase in pressure drop and a decrease in permeate production in a membrane filtration installation (Shannon et al., 2008; Vrouwenvelder et al., 2011).

Several strategies have been implemented to control biofouling in RO and NF systems, some focus on cleaning by chemicals (Baker and Dudley, 1998; Madaeni et al., 2009; Majamaa et al., 2010; Ridgway and Flemming, 1996; Subramani and Hoek, 2010) or novel approaches like air-water flushing (Cornelissen et al., 2010, 2007), while others aim at reducing the impact of biofouling on performance by modifying the system design (Vrouwenvelder et al., 2010). Feed spacers are important for maintaining inter-membrane space and enhancing mass transfer in membrane systems. However, in the presence of feed spacers biofouling has shown to cause a stronger impact on membrane performance (Tran et al., 2007; Vrouwenvelder et al., 2009).

In the past, research has focused on modifying feed spacers design and/or material, mainly to improve water permeation (Cao et al., 2001; Subramani et al., 2006). Membranes and feed spacers with antifouling coatings to prevent attachment and growth of bacteria have been produced and tested (Pontie et al., 2012; Araújo et al., 2012; Miller et al., 2012; Ronen et al., 2015). The surface modification of membranes and spacers does not last for long either due to detachment of antifouling coating/material in time or due to formation of a conditioning biofilm layer on the membrane and feed spacer (Habimana et al., 2014; Suwarno et al., 2016).

An emerging approach is to produce geometrically modified feed spacers to obtain a lower pressure drop increase caused by biofouling compared to feed spacers currently applied. Numerical modeling has been used to (i) create modified geometries of feed spacers and (ii) evaluate their flow behaviour (Schellenberg and Sharpe, 2016; Bucs et al., 2015; Fimbres-Weihs and Wiley, 2010; Madireddi, 1999; Picioreanu et al., 2009; Wiley and Fletcher, 2002) as well as biofouling of the modified feed spacers (Bucs et al., 2014). In addition to numerical studies, experimental studies are essential to understand biofouling development due to the complex effect of biofilms on membrane performance. With the aid of numerical models, favourable geometries of feed spacers can be selected and produced by a conventional spacer manufacturing technique (Brian, 1960) or by novel methods like three-dimensional (3D) printing (Lee et al., 2016; Siddiqui et al., 2016) and tested under well-controlled conditions. The membrane fouling simulator (MFS) is a device suitable for biofouling studies, giving comparable results as large-scale membrane installations (Vrouwenvelder et al., 2007). MFSs enable to study biofouling development over the feed channel without permeate production, since permeate production has shown to have no effect on the feed channel pressure drop development in biofouling studies with NF and RO membrane systems (Vrouwenvelder et al., 2009, 2007).

The objective of this study was to evaluate the biofouling potential of modified feed spacers by performing hydraulic characterization and biofouling studies in membrane fouling simulators. The novelty of this study is a comparison between hydraulic resistance of clean spacers and biofouling impact of feed spacers under well-controlled conditions involving (i) short-term biofouling studies with biodegradable nutrient dosage and (ii) long-term biofouling studies without nutrient dosage.

2. Material and methods

2.1. Feed spacers

Six feed spacers were used in the studies (Table 1). Two reference feed spacers (coded *CON-1* and *CON-3*) were provided by Conwed Plastics (Minneapolis USA) with the same filament shape and internal strand angle (β) of 90° but different spacer thickness of 34 mils (~863 μm) and 31 mils (~787 μm) respectively (Fig. 1A and B). Four modified feed spacers were provided by DOW, Hydranautics, and Lanxess. Which aspects of the feed spacer geometry where changed is not fully clear. The companies DOW, Hydranautics and Lanxess, providing the feed spacers, reported that the feed spacers were modified, but did not specify in what respect the spacers were modified because of company policies. CT scanning of the feed spacer geometries involved in this study has shown differences (Haaksman et al., 2016). The DOW spacer had an internal contact angle of 70% while the contact angle for the other spacers was 90% (Table 1). The DOW spacer (DOW) had a uniform filament thickness throughout (Fig. 1C). HYD (Hydranautics, Oceanside USA) was designed with thinner regions around filament intersections (Fig. 1D). The HYD spacer had a larger average parallel strand distance. LXS-ASDi and LXS-ASD (Lanxess, Bitterfeld Germany) had alternating thick and thin filaments with LXS-ASDi having irregularity in the filament shape along its length (Fig. 1E and F). The LXS-ASDi and LXS-ASD spacers had besides the alternating spacer strands a larger average parallel strand distance (Table 1). The feed channel porosities for the spacers were calculated based on CT-scan measurements of the feed spacers (Supplementary Material Table S1) presented by Haaksman et al. (2016). All feed spacers consisted of polypropylene with density (ρ) 0.91 g cm^{-3}.

2.2. Experimental set-up

In all experiments, MFSs with membrane and spacer sheet dimensions of 20 cm × 4 cm were used. The MFS flow channel dimensions were 20 cm × 4 cm × 863 μm. *CON-3* had a deviating channel height: 787 μm. Coupons of feed spacer and membrane were placed in the MFS resulting in the same spatial dimensions as in spiral-wound membrane elements. The installation consisted of two cartridge filters in series (10 μm pore-size), flow controllers, nutrient dosage pump, MFSs and a back-pressure valve (Supplementary Material Fig. S1). Six identical MFSs were operated in parallel, simultaneously. The development of fouling was monitored by measuring the pressure drop increase over the feed spacer channel of the MFS and by analysing of sheets of membrane and spacer taken from the monitor for adenosine triphosphate (ATP) measurements to quantify the amount of accumulated active biomass at the end of the study. In addition, visual observations were made using the MFS sight window prior to membrane and spacer sampling. During operation, the MFS window was covered with a light-tight lid to prevent growth of phototrophic organisms.

2.3. Operating conditions

The hydraulic characterization of the six feed spacers was carried out in MFSs by measuring the feed channel pressure drop at water flow rates ranging from 10 L h^{-1} to 20 L h^{-1} (equivalent to linear flow velocities of 0.09 m s^{-1} to 0.18 m s^{-1}). The MFSs were operated at a pressure of 1.70 bar to avoid degassing.

To study biofilm development in the MFS, water was pumped to