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Fouling resilient perforated feed spacers for membrane filtration

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ABSTRACT

The improvement of feed spacers with optimal geometry remains a key challenge for spiral-wound membrane systems in water treatment due to their impact on the hydrodynamic performance and fouling development. In this work, novel spacer designs are proposed by intrinsically modifying cylindrical filaments through perforations. Three symmetric perforated spacers (1-Hole, 2-Hole, and 3-Hole) were in-house 3D-printed and experimentally evaluated in terms of permeate flux, feed channel pressure drop and membrane fouling. Spacer performance is characterized and compared with standard no perforated (0-Hole) design under constant feed pressure and constant feed flow rate. Perforations in the spacer filaments resulted in significantly lowering the net pressure drop across the spacer filled channel. The 3-Hole spacer was found to have the lowest pressure drop (50%–61%) compared to 0-Hole spacer for various average flow velocities. Regarding permeate flux production, the 0-Hole spacer produced 5.7 $L\,m^{-2}.h^{-1}$ and 6.6 $L\,m^{-2}.h^{-1}$ steady state flux for constant pressure and constant feed flow rate, respectively. The 1-Hole spacer was found to be the most efficient among the perforated spacers with 75% and 23% increase in permeate production at constant pressure and constant feed flow, respectively. Furthermore, membrane surface of 1-Hole spacer was found to be cleanest in terms of fouling, contributing to maintain higher permeate flux production. Hydrodynamic understanding of these perforated spacers is also quantified by performing Direct Numerical Simulation (DNS). The performance enhancement of these perforated spacers is attributed to the formation of micro-jets in the spacer cell that aided in producing enough unsteadiness/turbulence to clean the membrane surface and mitigate fouling phenomena. In the case of 1-Hole spacer, the unsteadiness intensity at the outlet of micro-jets and the shear stress fluctuations created inside the cells are higher than those observed with other perforated spacers, resulting in the cleanest membrane surface.

1. Introduction and background

Water scarcity is rapidly emerging as an important concern across the globe. Membrane filtration processes are constantly evaluated regarding technological development to improve efficiency, minimize operation cost and to be more environmentally friendly (Amy et al., 2017). Spiral-wound membrane modules (SWM) are most commonly encountered in these membrane filtration processes for water treatment. These modules are rolled by stacking together alternating layers of membranes and spacers. Currently, the major constraints of their application are represented by the fouling, high concentration polarization and loss of pressure. The SWM performance can be improved by reducing these constraints which are primary linked to feed spacers design, membrane properties and operating conditions (Schwinge et al., 2002, 2004a).

The role of the feed spacer in SWM is not only to keep membrane sheets apart but also to generate feed flow unsteadiness/turbulence that aid in reducing the concentration polarization and thus resulting in higher permeate production (Gao et al., 2013). Conversely, it is also known that although the feed spacers can enhance the permeate production, it also elevates the pressure drop along the flow channel (Van Paassen et al., 1998), thereby increasing the water production cost. Several studies have also reported that the feed spacers promote biofilm growth close to spacer strands before spreading over the rest of the membrane area (Baker and Dudley, 1998; Tran et al., 2007; Vrouwenvelder et al. 2009a, 2009b). Fouling (inorganic, organic and biological) phenomenon is considered as the most significant factor which affects the performance of the membrane filtration process with time

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(Salvador Cob et al., 2012; Tang et al., 2011) as they result in permeate flux decline and an increase in pressure drop across the filtration module (Bicknell et al., 1985; Bucs et al., 2014; Ghaffour, 2004).

Therefore, the major challenge for most membrane filtration processes is to improve permeate flux and minimize the pressure drop. The primary constraint associated with this challenge is the irreversible fouling of various organic, inorganic and biological materials. Although attempts to externally control the (bio)fouling development (air bubbling, modification of membrane materials, operating conditions, chemical cleaning) (Baker and Dudley, 1998; Bucs et al., 2014; Lee et al., 2011; Qaisrani and Samhaber, 2011) are made but are limited to varied applications and require additional control processes. As a result, depending on the application, spacers with optimum design are carefully chosen to align with the operation requirements (Da Costa et al. 1991, 1994; Koutsou et al., 2007). The modification of the spacer design thus remains a challenge for research works to improve the hydraulic and fouling conditions.

Experimental and numerical works on feed spacer of spiral-wound modules are focused on predicting the effect of spacer orientation and design (internal strand angle, strand thickness, filament size and porosity) (Da Costa et al., 1993; Fárková, 1991; Liu et al., 2013; Schock and Miquel, 1987; Vrouwenvelder et al., 2009b). The orientation of the spacers influences both the hydrodynamic conditions and the fouling throughout the spacer cells (Da costa and Fane, 1994; Geraldes et al., 2002a; Geraldes et al., 2002b; Neal et al., 2003; Radu et al., 2014). Da Costa et al. (Da costa and Fane, 1994) reported that spacers which promote a zigzag flow direction (diamond-type) are less efficient for mass transfer enhancement than those producing a straight flow (ladder-type). Similar insight was observed by Neal et al., (2003) where they utilized a feed latex suspension to investigate particle deposition on ultrafiltration membrane and found that the deposition depends on the spacer positioning. They concluded that the spacer orientation of 90° against the mean flow could aid in the reduction of fouling and the enhancement of flux due to a significant change in local hydrodynamics at the elemental level because of eddy formation and turbulent production.

Besides the orientation of spacer-filled channel, several geometrical parameters have been optimized concerning fluid and contaminant behaviors. Schwinge et al., (2004b) investigated the effect of layers of spacers on the permeate flux and pressure drop. With UF membrane, the 3-layer spacer reveals an enhancement of mass transfer and less fouling tendency despite the increase of pressure drop when compared to the 2-layer spacer setup. Haaksman et al., (2017) also demonstrated the improvement of spacer performance by alternating strand thickness, to generate high shear stress on the membrane which leads to the reduction of the concentration polarization.

Several studies focused on modifying the internal strand angle (angle between two adjacent filaments) of spacers to assess its impact on the hydrodynamics. Decreasing the internal strand angle is beneficial in reducing the hydraulic resistance that leads to minimization of energy consumption (Haaksman et al., 2017; Koutsou et al., 2007; Siddiqui et al., 2016). However, the shear stress (and associated mass transfer) tends to decrease as well (Koutsou et al., 2007). Furthermore, for high L/D ratio (L represents the distance between the parallel filaments and D is the filament diameter) of the spacer the same behavior is observed (Koutsou et al., 2007; Saeed et al., 2015). Recently, Siddiqui et al., (2016) tested the spacer performance in the Membrane Fouling Simulator (MFS) by altering the spacer mesh size (number of spacer filaments per unit area) and contact angle of standard spacer. For the same amount of biomass accumulated, the modified spacer showed 34% lower increase on pressure drop over the filtration system.

Spacer filament shape optimization has also been investigated in the past to assess the role of hydrodynamics on fouling and concentration polarization (Cao et al., 2001; Fritzmann et al., 2013, 2014; Subramani et al., 2006). Subramani et al., (2006) studied filament positioning for the cavity, submerged and zigzag configurations. The cavity configuration was found to have lowest pressure drop compared to zigzag and submerged configurations. However, the zigzag configuration was found to have potential to promoting fouling and scaling due to the development of dead zones. Ahmad et al., (2005) evaluated three different filament cross-sectional shapes (triangular, square and circular). The triangular filaments generated the highest turbulent intensity, resulting in lowest concentration polarization and an increase of mass transfer. However, concerning energy consumption, the circular filaments allows optimal performance when compared with triangular and square shapes of filaments. Jiuqing et al. (Liu et al., 2013) designed a novel spacer that can intrinsically perform static mixing of the flow within the feed channel. The static mixing spacer performance was found similar to that of woven fiber spacer. At lower power inputs, an enhanced mass transfer coefficient was observed for mixing spacer design. Clemens et al. (Fritzmann et al. 2013, 2014) also investigated a helical microstructure spacer that resulted in significant improvement of overall mass transfer. However, only mass transfer was investigated but performance of helical spacer for fouling was not.

From an experimental perspective, the characteristic dimensions of the feed spacers present challenges to explore the hydrodynamics and associated biological and chemical phenomena occurring at an elemental level. Computational Fluid Dynamic (CFD) is therefore widely applied as a complementary technique to model the fluid flow behavior across the membrane/spacer system (Bucs et al., 2015; Cao et al., 2001; Dendukuri et al., 2005; Fimbres-Weihs and Wiley, 2007; Karode and Kumar 2001). Based on flow condition, spacer design, and orientation, the CFD tool allows simulating the hydrodynamic conditions which can be advanced by coupling biological and chemical process to predict fouling and mass transfer (Cao et al., 2001).

Although quite a bit of research efforts on controlling fouling through external mechanics are proposed, fewer research efforts are focused on controlling fouling through a change in the intrinsic design of feed spacers (Fritzmann et al. 2013, 2014; Liu et al., 2013). The present work focuses on fundamentally changing the intrinsic design of feed spacer by perforating the spacer filament. It was hypothesized that at an elemental level, these perforations provide micro-jets inside the filament cell producing high shear at the membrane surface. This high shear produced by these micro-jets has potential to sweep away or avoid the foulants to deposit on the membrane surface and improve the permeate flux. Further, the introduction of perforations in spacer filaments increases the feed channel porosity, which helps in reducing the net driving pressure and pressure drop which eventually reduces the energy consumption. To evaluate the hypothesis of perforations, CFD calculations where first performed to optimize the feed spacer design for higher unsteadiness and high membrane shear in the hydrodynamics context (Ghaffour and Qamar 2016).

The novel perforated feed spacer design intrinsically controls the hydrodynamics that has potential to minimize fouling without any additional external controls. It substantially makes it useful for all applications in membrane filtration processes under various feed type and operating conditions. Three types of symmetric perforated spacers are tested (1-Hole, 2-Hole, and 3-Hole) against the no perforated spacer (0-Hole). All spacers were in-house designed and fabricated by 3D-printer technology and evaluated for hydraulic characterization and fouling potentials. The fundamental hydrodynamic was also evaluated for each spacer design