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Graphical abstract

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.

Keywords: Novel design spacers, CFD, Filtration, Perforated spacers, Fouling, Optical Coherence Tomography (OCT).

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](#), [Schwinge et al. 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, Vrouwenvelder et al. 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 (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, Da Costa et al. 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. \(Neal et al. 2003\)](#) 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. \(Schwinge et al. 2004b\)](#) 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. \(Haaksman et al. 2017\)](#) 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. \(Siddiqui et al. 2016\)](#) 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](#), [Fritzmann et al. 2014](#), [Subramani et al. 2006](#)). [Subramani et al. \(Subramani et al. 2006\)](#) 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. \(Ahmad et al. 2005\)](#) 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. \(Fritzmann et al. 2013, Fritzmann et al. 2014\)](#) 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, Fritzmann et al. 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 were 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 using CFD approaches to gain insight into local hydrodynamics and related performance.

2. Materials and methods

The details of the feed spacer design and manufacturing technique, experimental setup, flow parameters and numerical formulation are presented in this section. Numerical assumptions utilized in the present work are in-line with experiments and are valid for the investigated parametric range.

2.1. Feed spacers

The Computer Aided Design (CAD) of a symmetric feed spacers was carried out in SolidWorks software (Dassault Systems SOLIDWORKS Corporation, Waltham, Massachusetts, USA, Version 2016) by extruding circular cross-section to either cylindrical or conical section of varying length. Spacer characteristic angles, the angle between the crossing filament (strand angle) α , and the incident flow angle β , are both fixed to 45° and 90° for all the cases investigated (Fig. 1). The manufacturing of the feed spacers was carried out using a high-resolution 3D-printing technology. The CAD design was directly imported to a 3-D printer (MiiCraft 125, Version 3.4.5, MiiCraft

Inc.) for rapid prototyping. This technique allowed to print a complicated design of perforated feed spacers accurately with a high resolution (25-micron printing layer). The printing was achieved by polymerization of liquid resin (Acrylate Monomer, BV-007) activated by UV light source that produces strong and chemically inert material.

Fig. 1. Schematic representation of the feed spacer with all dimensions in mm. Perforations are shown by dashed lines and are placed at the center of the filament thickness (arrows indicate the flow direction).

Four symmetric spacer design were 3D-printed, (a) standard spacer with no perforation (0-Hole), (b) spacer with one hole at the filament intersection (1-Hole), (c) spacer with one hole at the filament intersection and one hole at the center of filament (2-Hole), and (d) spacer with one hole at the filament intersection and two holes on the filament (3-Hole). The characteristic dimension (diameter of the filament) was kept same for all the printed spacers. Figure 1 shows the schematic and typical dimensions of the spacer configuration. All the spacers were printed in the rectangular frame of 2.5 cm $\times$ 8 cm of support material and later the required size of the spacer area 6 cm $\times$ 1.5 cm was cut corresponding to fit the flow cell size. Figure 2 shows the CAD model of each spacer, along with the image of the 3D-printed spacer which was analyzed by Scanning Electron Microscope (SEM) imaging for dimension accuracy. Overall $\pm$ 5% dimension mismatch

181 on the smallest length scale of the spacer was observed when compared to the CAD model and the
 182 SEM images.

183
 184 **Fig. 2.** CAD models, photographs and SEM images of different 3D printed feed spacers.

185 186 2.2. Experimental setup

187 The schematic of the experimental setup is depicted in Figure 3. A customized cross-flow flow
 188 cell with a filtration area of 6 cm x 1.5 cm was utilized. An ultrafiltration (UF) membrane
 189 (STERLITECH, Synder flat sheet membrane, polyethersulfone, MWCO of 100 KDa) was used
 190 for all the experiments. The spacer and the membrane were placed in the flow cell channel which
 191 has a height of 1.2 mm on feed side. A screw pump (COLE-PARMER Instrument, Model 75211-
 192 70) was utilized to pump the feed solution. Two pressure gauge sensors (OMEGA, Model PX309-
 193 050G) were placed at the feed inlet and outlet of the flow cell module. These pressure sensors
 194 measure the applied pressure drop applied over the membrane module (ΔP_o). A pressure

differential transmitter was also installed to measure the pressure drop (ΔP) inside the feed channel where all spacers are installed (Fig. 3). The permeate flux was collected into the storage tank placed on a digital weight balance.

Fig. 3. Schematic of experimental setup with layout of various instruments used for experiments.

The whole setup was automatically controlled by data acquisition system (National Instruments, LabView, 2016). All the reading from the sensors and balance were continuously recording at an interval of 10 minutes. Membrane surface was monitored for fouling using an Optical Coherence Tomography (OCT) (THORLABS, HYPERION). Two-dimensional images of fouling were acquired at the center of the cell towards the end of the experiments. The raw data from the OCT software was exported in ImageJ software (U. S. National Institutes of Health, Maryland, USA) for post-processing.

2.3. Numerical Solution Methodology

Direct Numerical Simulation (DNS) approach was utilized to model the fluid flow over the various feed spacers design. Although DNS is computationally expensive, it allows temporal and spatial flow resolution to the smallest turbulent scales (Kolmogorov), without applying any turbulent models. The solution of direct Navier-Stokes equations with incompressible flow assumption was performed. The governing Navier-Stokes equations in non-dimensional form are given by:

$$\nabla \cdot (\vec{u}) = 0 \quad (1)$$

$$\frac{\partial(\vec{u})}{\partial t} + \nabla \cdot (\vec{u} \vec{u}) = -\nabla P + \nabla \cdot \frac{1}{Re} [\nabla \vec{u} + (\nabla \vec{u})^T] + \rho \vec{g} \quad (2)$$

where t represents time, $\vec{u}$ the velocity field vector, P the pressure and ∇ the three-dimensional space gradient and Re is the Reynolds number, $Re = \rho U_o H / \mu$ (based on the average inlet velocity, U_o , and channel thickness, H). The fluid is assumed to have characteristic of the Newtonian fluid. As the effect on hydrodynamics inside the channel with a spacer was only investigated, therefore, membrane surface was modeled as a solid wall. The channel walls are assumed to be impermeable that allowing the use of no-slip boundary condition. At the inlet and outlet of the channel, the pressure conditions as recorded during the start of the experiments were specified. In the spanwise direction, periodicity was enforced considering the symmetry of flow and filament cell repetition. The solution of the system of equations was done in a finite-volume framework and was carried out on a commercial solver ANSYS Fluent (ANSYS, Inc., Canonsburg, PA, USA) with the specified boundary conditions. The temporal discretization is performed by using second-order implicit formulation. Pressure formulation is also second order accurate while the momentum term in the governing equation follows the QUICK (Quadratic Upstream Interpolation for Convective Kinematics) formulation. The pressure-velocity couple was handled by PISO (Pressure Implicit with Split Operator) (ANSYS 2016) algorithm.

For all simulations the spatial domain was discretized approximately by 22 million grid points. As the resulting system of discretized equations is quite large, therefore, all the computations are carried out on the available KAUST Supercomputing facility (SHAHEEN II) (KAUST Supercomputing and Laboratory 2017). For all computation 1024 cores on Intel Haswell Processor (2 CPU socket per node, 16 cores per CPU, 2.3 GHz with 128 GB of memory per node) were utilized. The connectivity between the nodes was maintained by an advance Cray Aries interconnect technology with Dragonfly topology.

2.4. Synthetic Feed Solution

The characterization of perforated feed spacers was focused on intrinsic hydrodynamics and its impact on overall flux production and associated fouling. A synthetic feed solution was prepared with the aim to stimulate fouling formation and growth on the system in a faster manner. The feed solution was formed by incubating 0.5 L of seawater at 30°C for 24 h with 0.5 g.L⁻¹ of Bacto™ Yeast Extract (Extract of Autolysed yeast cells, Becton Dickinson and Company), which acted as nutrient compound for the seawater bacteria. After 24 h, the solution was diluted with 1.5 L of seawater along with 0.1 g.L⁻¹ of alginic acid sodium salt (Sigma-Aldrich) and 0.25 g.L⁻¹ of xhantan gum (Sigma-Aldrich). The solution was then stirred for 4 hours with a magnetic stirrer at 300 RPM. A total of 2 L solution was prepared for each set of experiments, and the quantity was found to be sufficient for each experiment.

3. Results

The performance of various perforated feed were carried out by studying the hydraulic behavior, flux and fouling development on the membrane surface. Two sets of experiments were mainly

performed to characterize spacer performance. In the first set of experiments, the flow cell was operated under constant initial driving pressure ($\Delta P_o \approx 60 \pm 3$ KPa). However, the variation in initial driving pressure was quite small, and therefore this set of experiment was considered as constant pressure. In the second set of experiments, the flow cell was operated under constant feed flow rate ($Q = 12 \text{ L.h}^{-1}$). Both these tests were aimed to envisage the performance of novel perforated spacers against the standard spacer (no perforation) at various flow conditions. The objective of evaluating the performance of these perforated spacers under these two conditions (constant pressure and constant flux) were primarily done because different spacer designs were tested and compared simultaneously. The constant pressure evaluation ensures that all feed spacers are evaluated for the same transmembrane filtration pressure, which explicitly evaluate the improvement in permeate flux and fouling associated with each spacers design. Under constant flux condition (typical industrial operation mode), the transmembrane pressure variation depends on the type of spacer design. It is anticipated that more perforations will result in lower transmembrane pressure as the flow channel porosity decreases. Therefore, the constant flow rate would essentially evaluate the spacers design performance under industrial operation mode for varying transmembrane pressure, consequently the energy consumption of the filtration process.

3.1. Performance under constant pressure across the module

Under constant feed pressure case, spacers were exposed to the same initial feed pressure across the flow cell ($\Delta P_o \approx 60 \pm 3$ KPa). All experiments were conducted for 48 h. The time frame was sufficient for developing fouling and to achieve steady permeate flux output. Figure 4.A depicts the variation of permeate flux over time for all the four spacers. A decline in permeate flux is observed until a steady state is achieved. The 0-Hole spacer produced approximately 5.67 L.m^{-2}

$2. \text{h}^{-1}$ of permeate flux under steady operations, whereas 1-Hole, 2-Hole and 3-Hole produced 9.91 $\text{L.m}^{-2}.\text{h}^{-1}$, 8.67 $\text{L.m}^{-2}.\text{h}^{-1}$ and 6.66 $\text{L.m}^{-2}.\text{h}^{-1}$, respectively. The feed spacer with 1-Hole produced the highest overall flux, followed by 2-Hole and 3-Hole when compared to the 0-Hole spacer. Further, the initial flux for all perforated spacer was also found to be higher when compared to the standard 0-Hole spacer. Percentages of flux enhancement compared to 0-Hole spacer are plotted in Figure 4.B. For 1-Hole spacer, it was found the flux recovery is approximately 75% for 1-Hole, followed by 53% for 2-Hole and 17% for 3-Hole. The data indicates that spacer perforation significantly improves the filtration performance and 1-Hole spacer appears to be most effective.

Fig. 4. Filtration performance of perforated spacers at constant initial pressure (60 KPa) across the filtration module. (A) Permeate flux as a function of time, and (B) Flux enhancement relative to 0-Hole spacer for all perforated spacers when steady state is achieved.

The decline of flux is primarily associated to the concentration polarisation and membrane fouling (Li et al. 2016, Madaeni 1999, Schock and Miquel 1987, Vrouwenvelder et al. 2008,

Vrouwenvelder et al. 2009a, Vrouwenvelder et al. 2009b). OCT scanning technique was utilized to investigate the fouling behavior to envisage the effect of perforation on the steady fouling. Two-dimensional OCT scans were taken on a fixed filament cell location (center of the cell, aligned with the flow direction) on the membrane surface after the permeate flux reaches a steady state. Figure 5 shows the OCT images obtained for all spacers at 40 h operation. The OCT scan includes three sections, the active layer of membrane (bright line in center), the porous UF membrane (bottom below active layer) and the fouling (on top of the active layer). The 0-Hole spacer was found to have the highest fouling (thickness = $159 \pm 3 \mu\text{m}$) for the same feed and under the same operating conditions (constant ΔP_o).

Fig. 5. OCT scans for fouling taken on the membrane surface after 40 h of operation at constant ΔP_o for all spacers.

The novel perforated feed spacers with holes drastically hamper the growth of fouling under the same operating conditions. Among the three spacers, 2-Hole and 3-Hole spacers show very

little fouling compared to the 0-Hole spacer. However, 1-Hole spacer has shown minimum fouling, and the membrane surface appears to be completely clean. Therefore, the flux enhancement for all the spacers, as seen in Figure. 4.B, is attributed to the intrinsic cleaning of the membrane surface by perforations in the spacer elements.

3.2. Performance under constant feed flow

Figure 6.A shows the permeate flux as a function of time for all spacers. The trends are similar to the case of constant pressure. For all spacers, the flux production decreases with time (Fig. 6.A). The highest permeate flux in steady conditions was obtained for 1-Hole spacer with average flux of $8.15 \text{ L.m}^{-2}.\text{h}^{-1}$ followed by 2-Hole, $7.91 \text{ L.m}^{-2}.\text{h}^{-1}$, 3-Hole, $6.74 \text{ L.m}^{-2}.\text{h}^{-1}$ and 0-Hole, $6.61 \text{ L.m}^{-2}.\text{h}^{-1}$ spacer, respectively. Compared to 0-Hole, the permeate flux enhancement for 1-Hole, 2-Hole, and 3-Hole spacers was found to be 23%, 20%, and 2%, respectively (Fig. 6.B). These values are lower in magnitude when compared to the constant initial pressure case. This is attributed to the higher pressure drop across the filtration module for the constant pressure operation mode.

Fig. 6. Filtration performance of perforated spacers at constant feed flow rate (12 L.h⁻¹). (A) Permeate flux as a function of time, and (B) Flux enhancement relative to 0-Hole spacer for all perforated spacers when steady state is achieved.

Figure 7 shows the fouling behavior of all the spacers investigated under constant feed flow rate. The OCT scans were taken at 40 hours when flux reaches a steady state. The fouling trend is found to be similar as seen for constant initial pressure case. The membrane covered by 0-Hole spacer has significant fouling with an estimated thickness of $92 \pm 9 \mu\text{m}$. The 1-Hole spacer membrane surface is found to have the lesser fouling followed by 2-Hole and 3-Hole spacers as seen for constant pressure case.

Fig. 7. OCT scans for fouling taken on the membrane surface after 40 hours of operation at constant feed flow rate for all spacers.

3.3. Pressure drop for perforated spacers

In order to investigate the effect of perforated design on the hydraulic resistance, feed channel pressure drop measurements were carried for all the spacers. Figure 8.A shows the pressure drop as a function of average cross-flow velocities. As the channel average flow velocity is increased the corresponding pressure drop increases and appears to follow quadratic behavior. For average velocities commonly used in practice, i.e. $U = 0.173 \text{ m.s}^{-1}$ (corresponds to average effective velocity of 0.162 (Vrouwenvelder et al. 2009a)), 0-Hole spacer has a pressure drop equal to 38.32 mbar against 32.49, 20.12 and 17.73 mbar for 1-Hole, 2-Hole and 3-Hole spacers, respectively. As evident, the perforated spacers contributed in minimizing the energy consumption when compared to no perforated spacer. This decrease in pressure drop appears more significant when the number of holes in the spacer filaments is increased. This is attributed to an increase in channel porosity as the number of perforations increases. Thus, the 3-Hole spacer performs best in terms of energy consumption (less pressure drop), followed by 2-Hole, 1-Hole and 0-Hole spacers, respectively.

Fig. 8. Hydraulic resistance characterization for all spacers. (A) Feed channel pressure drop (ΔP) as a function of average cross-flow velocity, and (B) Percentage reduction of feed pressure drop relative to 0-Hole at three various velocity rates (0.069, 0.173 and 0.279 m.s⁻¹).

Figure 8.B shows the percentage decrease of pressure drop against the 0-Hole spacer at three different velocities (low, moderate and high velocities). The highest decrease in pressure drop is observed for 3-Hole spacer at all velocities. The percentage decrease reaches 61%, 54% and 50% at average flow velocity of 0.069, 0.173 and 0.279 m.s⁻¹, respectively. For 2-Hole spacer the pressure drop is also significant (61%, 47% and 42%), whereas for 1-Hole spacer the pressure drop is least (33%, 15% and 9%). Although the pressure drop is least in 1-Hole spacer, it produces the highest flux and keeps the cleanest membrane surface. Furthermore, it is also observed that for the same perforated spacer, increasing feed velocity results in lowering the percentage decrease of pressure drop (Fig. 8.B), indicating that the perforated spacer performs optimal in terms of energy consumption at lower average feed velocities.

4. Discussion

The performance characterization of the novel perforated feed spacers indicates that the perforations can lead to improvement in the permeate flux. For both operating conditions, either under constant initial pressure or constant feed flow rate the 1-Hole feed spacer performance was better than the other feed spacers. It ensures a higher permeate flux by consuming low operating energy (lower feed channel pressure drop). Moreover, this spacer enables to mitigate the growth of organic and biological fouling on the membrane surface. Therefore, it contributes in reducing several operating expenditures of the filtration process, such as, frequent backwashing and chemical cleaning that ultimately increases the life of membrane module (Meng et al. 2009, Qaisrani and Samhaber 2011). The OCT scans clearly indicate that these perforated spacers tend to minimize/eliminate fouling on the membrane surface quite effectively.

The experimental evaluation of perforated spacers shows that the role of hydrodynamics is critical and primarily controls the overall filtration performance. To elucidate the fundamental hydrodynamics occurring at the elemental level of the novel feed spacers, a Direct Numerical Simulation (DNS) approach was utilized. Two spacer cells as well as two half spacer cells were extracted from the 3D-printed CAD design. Simulations were performed for constant feed flow rate ($Q = 12 \text{ L.h}^{-1}$) to elaborate fundamental changes in hydrodynamics associated with various spacer perforations.

Figure 9 shows the non-dimensional velocity magnitude of all spacers at the central plane of the feed channel. For 0-Hole spacer, the incoming fluid gets divided into two streams by the cylindrical filaments intersection. These two incoming fluid streams merge to form a thin shear layer (under steady conditions, as schematically explained in Figure 10.a) at the center of the cell. Depending on the magnitude of the incoming flow velocity and the filament geometry this shear layer breaks down to form small-scale eddies which ultimately transit to the turbulent regime as shown in the schematic of Figure 10.b. For the given constant flow rate ($Q = 12 \text{ L.h}^{-1}$), 0-Hole spacer has a full turbulent signature (Fig. 9.a). However, as the holes are introduced, the turbulent intensity increases for 1-Hole spacer, whereas, it decreases significantly for 2-Hole and 3-Hole spacers (Fig. 9.c and 9.d).

Fig. 9. Non-Dimensional velocity magnitude for different spacers at central plane of the feed channel from DNS calculation (flow direction from top to bottom).

The major performance booster for the perforated spacers is the formation of micro-jets inside the spacer cell. For 0-Hole case, the intersection of filament obstructs incoming feed flow as the intersection serves as supporting base for the tightly placed membranes. As no flow pass over the filament intersection, the downstream side is exposed to the lowest velocities and thus lowest shear. These zones are generally called dead zones or recirculating vortex (Fig. 10.a and b), and potentially serve as the location for organic/inorganic particle deposition. If the inflow feed velocity is increased, these dead zones are perturbed by shear layer, and ultimately goes through the transition to an unsteady regime, and under higher flow rate flow transition to the turbulent state occurs (Fig. 9.b). For commercial spacers it has been demonstrated (Bucs et al. 2015) that if the inlet flow velocity is less than 0.16 m/s the flow inside the channel remains steady, whereas, transition occurs if the inlet velocity is further increased from 0.16 m/s, resulting in

unsteady/turbulent flow. However, to achieve unsteady or turbulent state inside the filament cell, an additional operating cost is required in terms of energy consumption due to higher pumping energy.

Fig. 10. Schematics illustrating the fluid behavior at different states: (a) fluid flow under steady flow conditions, (b) under turbulent condition for 0-Hole spacers, and (c) turbulent state in presence of perforated spacer (1-Hole).

By default, the perforated spacer overcomes this hurdle by eliminating the dead zones behind the filament intersection (Fig. 10.c). In case of the perforated spacers, as the fluid enters the filament holes the velocity magnitude increases (area constriction, Bernoulli effect ([White 1998](#))), and therefore, a micro-jet is formed at the exit of the hole. In case of 1-Hole spacer, the micro-jet exit velocity reaches a magnitude of 4.5 – 5.5 times the inlet velocity (Fig. 9.b), whereas, for 2-Hole and 3-Hole spacers it reaches 2- 3 times (Fig. 9.c) and 1.3-2.3 times (Fig. 9.d), respectively. These micro-jets created at an elemental level within each spacer filament cell have sufficient

hydrodynamics force/shear that not only sweep away the dead zones but also any organic or inorganic foulants.

It is observed that as the filament perforations are increased, the micro-jets exit velocity magnitude decreases. It is attributed to the decrease in flow rate, due to the distribution of fluid momentum through the holes as the inlet feed momentum is fixed by operating the flow module at constant feed flow rate. For the constant flow rate, 1-Hole spacer has the highest micro-jet exit velocity, which is enough to transit the micro-jet from a steady state to an unsteady state (Fig. 9.a and b). As a result, the turbulent eddies formed at the downstream of the filament are further broken down by high-speed micro-jet inside the spacer cell, thus, intensifying the turbulent intensity for the case of 1-Hole spacer. Further, for the case of 2-Hole and 3-Hole spacers although micro-jet is present, but as they have lower exit velocities, the micro-jets remain steady in nature (Fig. 9.c and d). In addition, the fluid momentum downstream of the filament also decreases for perforated spacer as some quantity of fluid is now also diverted through the holes of the filament. It reduces the downstream momentum which results in minimizing the turbulent production within the spacer cell for the 2-Hole and 3-Hole spacers (Fig. 9.c and d).

Figure 11 shows an instantaneous non-dimensional wall shear stress contours for the bottom wall when the flow is fully developed inside the channel. For all the spacers, a high shear region is observed under the spacer filament. It is attributed to high-velocity gradients due to the attached vortex enveloping downstream of cylindrical filaments ([Chen et al. 1995](#)). This vortex can remain stationary or can undergo Von-Karman/turbulent shedding, depending on the flow velocity or the characteristic Reynolds number ([Chen et al. 1995](#)). Although the high magnitude of unsteady shear stress is essential to clean the surface of the membrane, high steady shear-stress value (like seen under filament) serves as seeding location for biofilm owing to higher bacterial attachment

possibilities (Lecuyer et al. 2011, Saur et al. 2017). However, to minimize biofilm attachment, a fluctuating unsteady shear-stress is required. For 0-Hole spacer, although the wall shear magnitude is fluctuating inside the spacer cell, a steady high shear-stress is present under the spacer element (Fig. 11.a) that potentially triggers the bacterial attachment and growth of biofilm over the membrane surface (Fig. 5 and Fig. 7). For 1-Hole spacer, the wall shear magnitude under the spacer filament is lower than 0-Hole spacer, and the shear-stress fluctuation inside the cell is also higher owing to unsteady micro-jet formation (Fig. 11.b). Thus, it results in minimizing biofilm growth on the membrane surface. For 2-Hole and 3-Hole spacers the steady shear stress magnitude under the cylindrical filament decreases further when compared to the 0-Hole and 1-Hole cases. However, the unsteady fluctuation of shear-stress inside the filament cell also decreases as turbulence is significantly reduced (almost steady state). As the magnitude of shear-stress is much lower under the spacer filament, the bacterial attachment is significantly reduced and thus biofilm formation is also minimized, even when flow inside the spacer cell is almost steady in nature. This trend is consistent with the experimental observations as seen through OCT scans and permeate flux data, with 0-Hole having the highest fouling and lowest flux whereas 1-Hole has lowest fouling and highest flux.

It has been clearly demonstrated that perforations in the spacer element clearly improve the feed spacer performance in terms of pressure drop and permeate flux recovery. The lower pressure drop and higher permeate flux associated with perforation are ideal in terms of reducing energy consumption. Although, the current work highlights the performance of novel perforated spacer for a typical synthetic feed, further tests are required with varying feed to test the performance of these spacers. In addition, the fouling and the permeate flux performance of these spacers need to be further investigated for different feed flow rates, membrane type, and at constant flux using a

larger filtration cell to mimic commercial operating conditions, to access its full potentials. Future work pertaining to these perforated spacers will be focused on these aspects and will aim to elucidate performance and fundamental dynamics in various filtration applications, including spiral wound nanfiltration and reverse osmosis modules.

Fig. 11. Non-dimensional shear stress contours for bottom wall in presence of various spacers (flow direction from left to right).

5. Conclusions

Three novel feed spacers with perforations in the filament were designed and successfully prototyped using 3D-printing technology. The hydrodynamic performance in terms of feed channel pressure drop and filtration efficiency were evaluated in an UF membrane system. Either under constant pressure drop or constant feed flow rate, the perforation in the filaments of spacers improves the filtration process. The performance gain in the filtration system is achieved by introducing micro-jets inside the filament cell through these perforations. These micro-jets not

only eliminate the dead zones inside the filament cell but also aid in redistributing/diffusing the shear stress to minimize bacterial attachment and thus significantly hamper the growth of fouling.

By utilizing these perforated spacers, the flux could be increased by 75% using the 1-Hole spacer which contributed to 15% reduction of pressure drop at typical operating velocity condition ($U = 0.173 \text{ m.s}^{-1}$). This reduction in pressure drop could be further increased to 54% when the number of perforation on the filament increases (3-Hole spacer). However, in this case the permeate flux enhancement was reduced to 17%. CFD simulations also indicate that increasing the number of perforations also reduces the fluid unsteadiness which result in fouling formation on the membrane surface. However, the fouling layer is much thinner than what is seen for the 0-Hole perforated (standard) spacer. 1-Hole spacer is found to perform best in terms of permeate flux production with minimum fouling on membrane surface but with least pressure drop. In conclusion, the perforation on feed spacer filament significantly improves the filtration performance and the magnitude of performance improvement depends on the operating conditions of the cross-flow filtration system.

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References

- Ahmad, A.L., Lau, K.K. and Abu Bakar, M.Z. (2005) Impact of different spacer filament geometries on concentration polarization control in narrow membrane channel. *Journal of Membrane Science* 262(1–2), 138-152.
- Amy, G., Ghaffour, N., Li, Z., Francis, L., Linares, R.V., Missimer, T. and Lattemann, S. (2017) Membrane-based seawater desalination: Present and future prospects. *Desalination* 401(Supplement C), 16-21.
- ANSYS, Inc. (2016) *Fluent Theory Guide*, Version 17; Southpointe, 275 Technology Drive, Canonsburg, PA 15317, USA.
- Baker, J.S. and Dudley, L.Y. (1998) Biofouling in membrane systems — A review. *Desalination* 118(1), 81-89.
- Bicknell, E.A., Dziewulski, D.M., Sturman, L.S. and Belfort, G. (1985) Concentration of Seeded and Naturally Occurring Enteroviruses from Waters of Varying Quality by Hollow Fiber Ultrafiltration. *Water Science and Technology* 17(10), 47-62.
- Bucs, S.S., Valladares Linares, R., van Loosdrecht, M.C.M., Kruithof, J.C. and Vrouwenvelder, J.S. (2014) Impact of organic nutrient load on biomass accumulation, feed channel pressure drop increase and permeate flux decline in membrane systems. *Water Research* 67, 227-242.
- Bucs, S.S., Valladares Linares, R., Marston, J.O., Radu, A.I., Vrouwenvelder, J.S. and Picioreanu, C. (2015) Experimental and numerical characterization of the water flow in spacer-filled channels of spiral-wound membranes. *Water Research* 87, 299-310.
- Cao, Z., Wiley, D. E., Fane, A.G. (2001) CFD simulations of net-type turbulence promoters in a narrow channel. *J. Membr. Sci.* 277, 157-176.
- Chen, J.H., Pritchard, W.G. and Tavener, S.J. (1995) Bifurcation for flow past a cylinder between parallel planes. *Journal of Fluid Mechanics* 284, 23-41.
- Da Costa, A.R., Fane, A.G., Fell, C.J.D. and Franken, A.C.M. (1991) Optimal channel spacer design for ultrafiltration. *Journal of Membrane Science* 62(3), 275-291.
- Da Costa, A.R., Fane, A.G. and Wiley, D.E. (1993) Ultrafiltration of whey protein solutions in spacer-filled flat channels. *Journal of Membrane Science* 76(2), 245-254.
- Da Costa, A.R., Fane, A.G. and Wiley, D.E. (1994) Spacer characterization and pressure drop modelling in spacer-filled channels for ultrafiltration. *Journal of Membrane Science* 87(1), 79-98.
- Da costa, A.R. and Fane, A.G. (1994) Net-Type Spacers - Effect of Configuration on Fluid-Flow Path and Ultrafiltration Flux. *Industrial & Engineering Chemistry Research* 33(7), 1845-1851.
- Dendukuri, D., Karode, S.K. and Kumar, A. (2005) Flow visualization through spacer filled channels by computational fluid dynamics-II: improved feed spacer designs. *Journal of Membrane Science* 249(1–2), 41-49.
- Fárková, J. (1991) The pressure drop in membrane module with spacers. *Journal of Membrane Science* 64(1), 103-111.
- Fimbres-Weihs, G.A. and Wiley, D.E. (2007) Numerical study of mass transfer in three-dimensional spacer-filled narrow channels with steady flow. *Journal of Membrane Science* 306(1–2), 228-243.
- Fritzmann, C., Hausmann, M., Wiese, M., Wessling, M. and Melin, T. (2013)

- Microstructured spacers for submerged membrane filtration systems. *Journal of Membrane Science* 446(Supplement C), 189-200.
- Fritzmman, C., Wiese, M., Melin, T. and Wessling, M. (2014) Helically microstructured spacers improve mass transfer and fractionation selectivity in ultrafiltration. *Journal of Membrane Science* 463(Supplement C), 41-48.
- Gao, Y., Haavisto, S., Tang, C.Y., Salmela, J. and Li, W. (2013) Characterization of fluid dynamics in spacer-filled channels for membrane filtration using Doppler optical coherence tomography. *Journal of Membrane Science* 448, 198-208.
- Geraldes, V., Semião, V. and de Pinho, M.N. (2002a) The effect of the ladder-type spacers configuration in NF spiral-wound modules on the concentration boundary layers disruption. *Desalination* 146(1), 187-194.
- Geraldes, V.t., Semião, V. and de Pinho, M.N. (2002b) Flow management in nanofiltration spiral wound modules with ladder-type spacers. *Journal of Membrane Science* 203(1-2), 87-102.
- Ghaffour, N. (2004) Modeling of fouling phenomena in cross-flow ultrafiltration of suspensions containing suspended solids and oil droplets. *Desalination* 167(Supplement C), 281-291.
- Ghaffour, N. and Qamar, A. (Apr. 5, 2016.) Fouling resistant membrane spacers. Patent Publication No. WO 2017/175137 A1, Oct. 12, 2017, Patent Application No. 62/318,543.
- Haaksman, V.A., Siddiqui, A., Schellenberg, C., Kidwell, J., Vrouwenvelder, J.S. and Picioreanu, C. (2017) Characterization of feed channel spacer performance using geometries obtained by X-ray computed tomography. *Journal of Membrane Science* 522, 124-139.
- Karode, S.K. and Kumar, A. (2001) Flow visualization through spacer filled channels by computational fluid dynamics I.: Pressure drop and shear rate calculations for flat sheet geometry. *Journal of Membrane Science* 193(1), 69-84.
- KAUST, Supercomputing and Laboratory (2017) Shaheen II-user guide. <https://www.hpc.kaust.edu.sa/>.
- Koutsou, C.P., Yiantsios, S.G. and Karabelas, A.J. (2007) Direct numerical simulation of flow in spacer-filled channels: Effect of spacer geometrical characteristics. *Journal of Membrane Science* 291(1-2), 53-69.
- Lecuyer, S., Rusconi, R., Shen, Y., Forsyth, A., Vlamakis, H., Kolter, R. and Stone, H.A. (2011) Shear Stress Increases the Residence Time of Adhesion of *Pseudomonas aeruginosa*. *Biophysical Journal* 100(2), 341-350.
- Lee, K.P., Arnot, T.C. and Mattia, D. (2011) A review of reverse osmosis membrane materials for desalination—Development to date and future potential. *Journal of Membrane Science* 370(1-2), 1-22.
- Li, S., Lee, S.T., Sinha, S., Leiknes, T., Amy, G.L. and Ghaffour, N. (2016) Transparent exopolymer particles (TEP) removal efficiency by a combination of coagulation and ultrafiltration to minimize SWRO membrane fouling. *Water Research* 102(Supplement C), 485-493.
- Liu, J., Iranshahi, A., Lou, Y. and Lipscomb, G. (2013) Static mixing spacers for spiral wound modules. *Journal of Membrane Science* 442(Supplement C), 140-148.
- Madaeni, S.S. (1999) The application of membrane technology for water disinfection. *Water Research* 33(2), 301-308.

- Meng, F., Chae, S.-R., Drews, A., Kraume, M., Shin, H.-S. and Yang, F. (2009) Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Research* 43(6), 1489-1512.
- Neal, P.R., Li, H., Fane, A.G. and Wiley, D.E. (2003) The effect of filament orientation on critical flux and particle deposition in spacer-filled channels. *Journal of Membrane Science* 214(2), 165-178.
- Qaisrani, T.M. and Samhaber, W.M. (2011) Impact of gas bubbling and backflushing on fouling control and membrane cleaning. *Desalination* 266(1-3), 154-161.
- Radu, A.I., van Steen, M.S.H., Vrouwenvelder, J.S., van Loosdrecht, M.C.M. and Picioreanu, C. (2014) Spacer geometry and particle deposition in spiral wound membrane feed channels. *Water Research* 64, 160-176.
- Saeed, A., Vuthaluru, R. and Vuthaluru, H.B. (2015) Impact of Feed Spacer Filament Spacing on Mass Transport and Fouling Propensities of RO Membrane Surfaces. *Chemical Engineering Communications* 202(5), 634-646.
- Salvador Cob, S., Beaupin, C., Hofs, B., Nederlof, M.M., Harmsen, D.J.H., Cornelissen, E.R., Zwijnenburg, A., Genceli Güner, F.E. and Witkamp, G.J. (2012) Silica and silicate precipitation as limiting factors in high-recovery reverse osmosis operations. *Journal of Membrane Science* 423-424, 1-10.
- Saur, T., Morin, E., Habouzit, F., Bernet, N. and Escudié, R. (2017) Impact of wall shear stress on initial bacterial adhesion in rotating annular reactor. *PLOS ONE* 12(2), e0172113.
- Schock, G. and Miquel, A. (1987) Mass transfer and pressure loss in spiral wound modules. *Desalination* 64, 339-352.
- Schwinge, J., Wiley, D.E. and Fletcher, D.F. (2002) A CFD study of unsteady flow in narrow spacer-filled channels for spiral-wound membrane modules. *Desalination* 146(1), 195-201.
- Schwinge, J., Neal, P.R., Wiley, D.E., Fletcher, D.F. and Fane, A.G. (2004a) Spiral wound modules and spacers: Review and analysis. *Journal of Membrane Science* 242(1), 129-153.
- Schwinge, J., Wiley, D.E. and Fane, A.G. (2004b) Novel spacer design improves observed flux. *Journal of Membrane Science* 229(1-2), 53-61.
- Siddiqui, A., Farhat, N., Bucs, S.S., Linares, R.V., Picioreanu, C., Kruithof, J.C., van Loosdrecht, M.C.M., Kidwell, J. and Vrouwenvelder, J.S. (2016) Development and characterization of 3D-printed feed spacers for spiral wound membrane systems. *Water Research* 91, 55-67.
- Subramani, A.K., S; Hoek, E. M. V (2006) Pressure, flow, and concentration profiles in open and spacer-filled membrane channels. *Journal of Membrane Science* 277, 7-17.
- Tang, C.Y., Chong, T.H. and Fane, A.G. (2011) Colloidal interactions and fouling of NF and RO membranes: A review. *Advances in Colloid and Interface Science* 164(1-2), 126-143.
- Tran, T., Bolto, B., Gray, S., Hoang, M. and Ostarcevic, E. (2007) An autopsy study of a fouled reverse osmosis membrane element used in a brackish water treatment plant. *Water Research* 41(17), 3915-3923.
- Van Paassen, J.A.M., Kruithof, J.C., Bakker, S.M. and Kegel, F.S. (1998) Integrated multi-

- objective membrane systems for surface water treatment: pre-treatment of nanofiltration by riverbank filtration and conventional ground water treatment. *Desalination* 118(1), 239-248.
- Vrouwenvelder, J.S., Hinrichs, C., Sun, A.R., Royer, F., van Paassen, J.A.M., Bakker, S.M., van der Meer, W.G.J., Kruithof, J.C. and van Loosdrecht, M.C.M. (2008) Monitoring and control of biofouling in nanofiltration and reverse osmosis membranes. *Water Science and Technology: Water Supply* 8(4), 449-458.
- Vrouwenvelder, J.S., Graf von der Schulenburg, D.A., Kruithof, J.C., Johns, M.L. and van Loosdrecht, M.C.M. (2009a) Biofouling of spiral-wound nanofiltration and reverse osmosis membranes: A feed spacer problem. *Water Research* 43(3), 583-594.
- Vrouwenvelder, J.S., Hinrichs, C., Van der Meer, W.G.J., Van Loosdrecht, M.C.M. and Kruithof, J.C. (2009b) Pressure drop increase by biofilm accumulation in spiral wound RO and NF membrane systems: role of substrate concentration, flow velocity, substrate load and flow direction. *Biofouling* 25(6), 543-555.
- White, F. M. (1998) *Fluid Mechanics*, 4 Har/Dsk edition; McGraw-Hill College.

Highlights

- A novel perforated spacer design is proposed.
- Spacer with one hole in the filament intersection showed the best performance.
- Recovery flux increased by 75% and pressure drop was significantly lower.
- OCT has been used to monitor the fouling layer during operation.
- DNS/CFD was used to understand the hydrodynamics.