Energy Efficient 3D Printed Column Type Feed Spacer for Membrane Filtration

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Abstract

Modification of the feed spacer design significantly influences the energy consumption of membrane filtration processes. This study developed a novel column type feed spacer with the aim to reduce the specific energy consumption (SEC) of the membrane based water filtration system. The proposed spacer increases the clearance between the filament and the membrane (reducing the spacer filament diameter) while keeping the same flow channel thickness as compared to a standard non-woven symmetric spacer. Since the higher clearance reduces the flow unsteadiness, column type nodes were added in the spacer structure as additional vortex shading bodies. Fluid flow behaviour in the channel for this spacer was numerically simulated by 3D CFD studies and then compared with the standard spacer. The numerical results showed that the proposed spacer substantially reduced the pressure drop, shear stress at the constriction region and shortened the dead zone. Finally, these findings were confirmed experimentally by investigating the filtration performances using the 3D printed prototypes of these spacers in a lab-scale filtration module. It is observed that the column spacer reduced the pressure drop by three times and doubled the specific water flux. 2D OCT (Optical Coherence Tomography) scans of the membrane surface acquired after the filtration revealed much lower biomass accumulation using the proposed spacer. Consequently, the SEC for the column spacer was found about two folds lower than the standard spacer.

Keywords

3D printing; Feed Spacer; SEC; Fouling; Pressure drop; CFD

1. Introduction

Spiral Wound Membrane (SWM) modules are dominant in water filtration processes. It comprises of filtration membrane layers separated by feed and permeate spacers. The primary purpose of a feed spacer is to support the membrane and create paths for the feed that stimulates the flow in the filtration channel (Da Costa et al., 1994; Koutsou and Karabelas, 2015). The unsteady flow hinders the foulant deposition on membrane/spacer surface and reduces concentration polarization, resulting in enhancement of permeate production. However, due to the creation of elevated flow obstruction feed channel, pressure drop increases (Dreszer et al., 2014; Horstmeyer et al., 2018) while promoting biofouling growth (Baek et al., 2014; Lecuyer et al., 2011; Saur et al., 2017; Vrouwenvelder et al., 2009) across the filtration feed channel. The specific energy consumption of the membrane filtration process is a function of both permeate flux and pressure drop, which are related to the spacer design. Therefore, the modification of spacer geometry has a crucial role in energy efficiency improvement. A better design can aid in reducing the pressure drop across the filtration channel which allows a higher flow rate (more linear channel velocity) for the same energy consumption to enhance unsteadiness to a desired level. Further, unique designs can be incorporated with the aim to minimize foulant deposition/growth inside the feed channel.

Significant research attention is drawn to improve the membrane filtration processes by tuning the feed spacer design. Before the introduction of proper prototyping tools, the effect of various commercial spacers by manipulating their orientation (ladder/diamond type spacers), thickness and filament spacing on the pressure drop and the water flux were experimentally investigated (Da Costa and Fane, 1994; Da Costa et al., 1993; Fárková, 1991). These studies found that the thicker filament spacer and the smaller filament spacing improved the mass transfer with a subsequent increase in the pressure drop. Furthermore, the maximum mass transfer was ensured when the spacer was orientated 90° against the mean feed flow, whereas the minimum

pressure drop was observed at 0° (Da Costa and Fane, 1994; Da Costa et al., 1993; Fárková, 1991). These studies only compared the performance of different commercial spacers without pursuing a fundamental change in the conventional spacer designs which can provide a significant impact on filtration performance.

Numerical studies have proposed efficient spacer designs, geometries, and arrangements (Amokrane et al., 2015; Han et al., 2018; Kaviani pour et al., 2017; Koutsou et al., 2007; Saeed et al., 2015; Saeed et al., 2012). The circular and elliptical shaped filaments reduced the hydraulic resistance compared to the other spacer geometries while the triangular and square filaments increased the mass transfer (Ahmad and Lau, 2006). Moreover, the woven type feed spacer configuration showed a higher mass transfer coefficient than the non-woven configuration, while reducing the pressure drop across the channel (Gu et al., 2017). These studies concluded that the feed spacers which showed a higher membrane shear stress reduces the organic and particulate fouling effects. In contrast, some other studies (Dai and Grace, 2010; Park et al., 2016) indicated that the excessive shear stress at the constriction zones (space between membrane and spacer filament) could significantly increase the fouling effect. A high shear stress resulting from the larger velocity gradient close to the membrane surface tends to deposit foulant particulates in this region. The high shear stress was further found to be responsible for promoting biofouling in membrane filtration systems (Lecuyer et al., 2011; Saur et al., 2017).

Recently, combined experimental and numerical studies were carried out to improve membrane filtration performance in terms of hydrodynamics and (bio) fouling. (Siddiqui et al., 2016) investigated the effect of the mesh-size and strand angle modifications (angle between two filaments) on the feed channel hydrodynamics and fouling using a 3D printed non-woven spacer design. 3D printing technology was used by (Fritzmann et al., 2014) to manufacture a

double helix spacer design which aided to increase 50% of the permeate flux that was attributed to higher pressure drop created by spacer design. In a proof of concept study, Sreedhar et al. developed a feed spacer with filaments based on triply periodic minimal surfaces (Sreedhar et al., 2018). This spacer increased the permeate flux and decreased the pressure drop inside the filtration channel to 20% and 5%, respectively. In another study, some symmetric perforated spacers were developed and the perforation effect was evaluated on reducing the pressure drop while augmenting the permeate flux production (Kerdi et al., 2018). Out of many perforated designs, it was demonstrated that the presence of a single perforation at the spacer filament intersection aids in improving the quantity of permeate flux production, lowering the pressure drop and removing the (bio)fouling from the filtration system. Consequently, the enhancement of water flux by these spacers does not ensure a substantial improvement in the energy efficiency of the process. For better energy efficiency, it is essential to design feed spacer that substantially minimizes the pressure drop, while maintaining unsteadiness with optimised shear stress in the feed channel to mitigate fouling.

The main objective of this study is to develop a feed spacer for the membrane-based filtration processes to reduce the specific energy consumption by optimizing the hydrodynamics of the feed channel. The optimization was achieved by considerably lowering the pressure drop and reducing the shear stress in the constriction zone. To reduce the pressure drop and shear stress, clearance between the spacer and the membrane was increased. The larger clearance was obtained by designing filaments of smaller diameter and connecting the filaments with column-type nodes symmetrically. Since the higher clearance reduces the unsteadiness (Ahmad and Lau, 2006), cylindrical column type nodes were proposed to create additional fluid recirculation zones to produce sufficient perturbation in the feed channel. Hydrodynamics of the feed channel for the column spacer is also computationally investigated and compared with a standard non-woven symmetric spacer. Direct numerical simulations (DNS) were carried out

for this hydrodynamic study. After elucidation of flow hydrodynamics at elemental level through the computational model, prototypes of the spacers were 3D printed. Furthermore, the filtration performances of the spacers for a membrane process were experimentally investigated in terms of foulant accumulation, pressure drop and permeate recovery using an ultrafiltration (UF) membrane. Fouling effects for the column spacer and the standard spacer were characterized by the in-situ observation of the fouling layer growth on the membrane surface after a certain period of operation using an optical coherence tomography (OCT) scanner. Finally, the experimental results were analyzed to compare the average pressure drop, specific flux and specific energy consumption for the two spacers.

2. Materials and Methods

This section outlines the preparation of synthetic feed solution as well as the methodologies used to evaluate numerically and experimentally the performance of the proposed column spacer in comparison with a standard non-woven symmetric spacer served as a reference. The calculation of various parameters relevant to this study is also highlighted in this section.

2.1. Feed Spacer Designs

Symmetric and column spacer designs were designed through Computer Aided Design (CAD) by using a commercial software CATIA (Dassault Systemes, Vélizy-Villacoublay, France). Table 1 represents the photographs and the CAD designs along with the dimensions of the column spacer compared to the standard spacer which is used as the reference. The standard symmetric spacer consists of circular non-woven shaped filaments arranged to each other at 90° as a strand angle. The diameter of these filaments is 1 mm, and the height of the nodes is 1.2 mm (spacer thickness). The clearance between the membrane and the spacer where space through which the feed solution can flow is estimated only 0.1 mm on each side of the filament. To increase this clearance, the column type spacer is proposed in this study. As the standard

122 spacer, this spacer has 1.2 mm of thickness, and it is also symmetric and non-woven with
123 circular shaped filaments organized at 90° as a strand angle.

124

125 **Table 1** Schematic diagram and the prototype of standard and column spacers with dimensions
 126 at various orientations.

	Standard Spacer	Column Spacer
Isometric View
Top View
Side View
Prototype
*Note: All dimensions are in mm.		

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However, it is characterized by thinner circular filaments, and cylindrical column shaped nodes having 0.5 mm and 1.5 mm as diameters, respectively. The clearance increases from 0.1 mm to 0.35 mm, compared to the standard spacer on each side of the filaments with keeping the same height of 1.2 mm for both designs cases. The final designs were 3D prototyped by using a Digital Light Processing (DLP) technology printer (MiiCraft 125, Rays Optics Inc., Hsinchu, Taiwan). The UV liquid resin used was an acrylate monomer (BV-007) allowed printing slice thickness of 50 μm for all models.

2.2. Numerical Approach

Hydrodynamics of the feed channel was computationally studied to compare the flow behaviours in presence of the proposed column and standard spacers. The spatial and transient distribution of pressure, velocity and shear stress in the feed channel were investigated by direct numerical simulation (DNS). Although the computational expense of DNS is quite high, it numerically solves the Navier–Stokes equations directly without assuming any turbulence model. Therefore, the accuracy of the solution is very high compared to the studies that assumed a steady-state or turbulence model for the theoretical analysis (Koutsou et al., 2007). Considering the feed as Newtonian fluid, governing equations (Continuity equation and Navier-Stokes equations) used for this study are given by:

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

$$\rho \left(\frac{\delta \mathbf{u}}{\delta t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = \rho \mathbf{g} - \nabla p + \mu \nabla^2 \mathbf{u} \quad (2)$$

where t and $\mathbf{u}$ represent the time and the velocity vector respectively, p stands for the pressure and ∇ is the spatial gradient. In addition to these, ρ and g are respectively the density of the fluid and its acceleration due to the gravity. The surface of the membrane was considered as a solid wall (Koutsou and Karabelas, 2015; Saeed et al., 2012; Siddiqui et al., 2016).

Unsteady computations were carried out for two full spacer filament and two half spacer filament cells (Table 1) to avoid the periodic boundary condition in the flow direction, which is considered as a major limitation of previous studies (Koutsou and Karabelas, 2015; Siddiqui et al., 2016). The fluid domain was discretized into 30 million control volumes following the grid refinement process. Appropriate physical boundary conditions were applied to the solution domain. At the inlet, a linear flow velocity corresponding to the experiments was specified, whereas, the outlet was kept at a fixed pressure value according to the experiments. No-slip boundary condition was enforced on the membrane surface and the periodic boundary condition was applied in the span-wise direction (Y-axis) due to the symmetry of the flow and the spacer geometry.

Finally, all governing equations were solved in the commercial fluid solver ANSYS FLUENT 2018. The second order time discretization was performed for the unsteady term. The pressure formulation which was also the second order with the convective term discretized using QUICK (Quadratic Upstream Interpolation for Convective Kinematics) approach. Pressure Implicit with Split Operator (PISO) scheme was used to couple pressure-velocity (ANSYS, 2013). As the resulted system of discretized equations was quite large, all the computations were carried out on the available Supercomputer (SHAHEEN II) by using 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).

2.3. Experimental setup

Performances of the designed spacers were experimentally studied in a cross-flow module of a membrane filtration process. As the UF membranes are highly prone to the fouling and widely used as the pretreatment process of the seawater desalination and wastewater treatment, UF membranes are used for the short term lab-scale experiments in this study. The schematics of the experimental setup with the various instruments used is shown in Fig. 1. A synthetic feed

solution with high fouling potential was prepared and utilized for all experiments. The setup
 comprised a feed solution tank, a magnetic stirrer, a feed circulation pump, a cross-flow cell
 containing the coupons of the membrane and feed spacer, a permeate collection tank and a data
 logging system. UF membrane with a filtration area of $6\text{ cm} \times 1.5\text{ cm}$ (Polyether sulfone,
 UP150, Mycrodyn Nadir, nominal molecular weight cut-off: 150 kDa) and feed spacer
 (standard/column) coupons were placed in a cross-flow module having a filtration channel with
 a height of 1.2 mm in the feed side.

Fig. 1. Schematic diagram of a lab-scale filtration setup.

A gear pump (Drive: Cole-Parmer, Model No: 75211-70; Head: N21) was used to circulate the feed solution into the flow cell at two different velocities (U_F) of 0.16 m/s (flow rate = 173 mL/min) and 0.18 m/s (flow rate = 203 mL/min) for two sets of experiments. This synthetic feed solution was continuously stirred using a magnetic stirrer to make sure that the foulants are homogeneously mixed in the feed tank. A gauge pressure sensor (OMEGA PX309-050G; Range: 0 to 3.5 bar, Accuracy: $\pm 0.25\%$, max) was used to monitor the feed inlet pressure while a digital differential pressure transmitter (OMEGA PX5200 M5091/0112; Pressure Ranges: 0 to 3.5 bar; Resolution: 0.1%) was utilized to measure the pressure drop (ΔP_{cell}) across the filtration module. The datasets provided by the sensors and the electronic weight balance were monitored through a data acquisition system (Labview 2016, National Instrument, USA) every one minute. The development of fouling in the filtration channel was observed in situ by Optical Coherence Tomography (OCT) (Thorlabs, Hyperion) at the end of each conducted experiment (48 h). The 2D-OCT images were then processed by using Image J software (National Institute of Health, USA).

2.4. Preparation of feed solution

To conduct a short term fouling experiment (48 h), a synthetic feed solution was prepared with aggravated fouling conditions following the procedure and component quantities used by Kerdi et al. (Kerdi et al., 2018). It composed of 2 L of total seawater containing 0.5 g/L of Bacto™ Yeast extract (extract of autolyzed yeast cells, Becton Dickinson and Company), 0.1 g/L of sodium alginate (Sigma-Aldrich) and 0.25 g/L of xhantan gum (Sigma-Aldrich). To prepare this solution, Bacto™ Yeast extract was added to 0.5 L of seawater and incubated at 30°C for 24 h to activate the growth of bacteria. This incubated solution was then mixed to 1.5 L of seawater in which the sodium alginate and the xhantan gum were dissolved and stirred for 24 h. Finally, the total 2 L seawater with high fouling potential was stirred at 300 rpm for 4 h by using a magnetic stirrer before being used as the feed solution for all our experiments.

2.5. Filtration performance parameters

The performance of the feed spacers is generally compared in terms of the permeate produced over filtration time. However, at the same operating conditions due to the differences in the hydraulic resistance of different feed spacers, transmembrane pressure and pressure drop across the channel are different. Indeed, the spacer that creates more hydraulic resistance in the channel rises the transmembrane pressure through the filtration membrane resulting in an increase of permeate flux. Simultaneously, as fouling occurs the pressure drop within the channel tends to increase the energy consumption of the system. Therefore, to compare the performance of different feed spacer designs, it is more accurate to verify the effect of the design modification on two intimately related parameters: the permeate flux and the pressure drop. Henceforth, the spacer performance in terms of specific flux and specific energy consumption is estimated in this study.

The specific flux is defined as the water flux produced by the filtration system causing the unit amount of pressure drop across the channel of the flow cell. It is calculated by;

$$J_w^s = \frac{J_w}{\Delta P_{cell}} \quad (3)$$

where, J_w is the permeate flux produced through the filtration membrane (LMH) and ΔP_{cell} represents the pressure drop (bar) monitored across the flow cell at the same time. The specific energy consumption (SEC) is defined as the energy consumed by the filtration system to produce the unit amount of the permeate flux. It is calculated by;

$$SEC = \frac{E}{Q_p} \quad (4)$$

where E represents the consumption of energy (kW) and Q_p is the rate of water permeation through the membrane (m³/h). The energy consumption is a function of the feed and the permeate flow rates, and the pressure drop obtained in both feed and permeate channels. As the permeate flows from the flow cell to the permeate collection tank due to the gravitational

force only, the energy consumed at the permeate side is assumed negligible in this study and the energy consumption is then given by;

$$E = \frac{1.667e^{-9} \times Q_F \times \Delta P_{cell}}{\eta} \quad (5)$$

where, Q_F denotes the volumetric feed solution flow rate (mL/min), ΔP_{cell} is the pressure drop across the test cell (mbar) and η is the feed pump efficiency (%). The efficiency of the feed circulation pump is assumed 100% for all the experiments carried out in this study.

Two different feed inlet velocities were selected to test the spacer designs. The common feed solution inlet velocity for filtration application is 0.16 m/s (Bucs et al., 2015). According to the cross-sectional area of the feed channel ($W \times H = 15 \text{ mm} \times 1.2 \text{ mm}$), it corresponds to inlet flowrate $Q_F = 173 \text{ mL/min}$. In addition, a little higher inlet velocity of 0.18 m/s corresponding to $Q_F = 203 \text{ mL/min}$ was also selected to test both spacers.

3. Results and Discussion

A novel column spacer design was proposed in this present work and evaluated for energy efficiency enhancement of the filtration process. It was achieved by reducing the fouling development and the hydraulic resistance inside the filtration system. In the first part, the hydrodynamics study in the presence of a column spacer was numerically carried out and compared with a standard symmetric spacer. In the second part, the performance of this novel column spacer in terms of the fouling potential, the specific flux and the specific energy consumption of the filtration system were experimentally tested in a lab-scale setup for a filtration process.

3.1. Hydrodynamics of the feed channel

Hydrodynamics of the feed channel was rigorously studied to investigate the spatial and transient distribution of the fluid flow parameters such as pressure, velocity and shear stress those define the fouling characteristics in the channel. Fig. 2 compares the simulated fluid pressure in the axial direction (x-axis) of the fluid flow for different inlet crossflow velocities (U_F) of feed solution using the column and standard spacers. It can be seen that for the standard spacer pressure drop per unit length (differential pressure drop (dp/dL)) was about six times higher than the column spacer at both velocities, $U_F = 0.16$ and 0.18 m/s. The differential pressure drop values for the standard spacer and the column spacer were 0.64 mbar/mm ($(11.50 - 1.85)/15$) and 0.11 mbar/mm at $U_F = 0.16$ m/s, while they were estimated 0.80 mbar/mm and 0.13 mbar/mm at $U_F = 0.18$ m/s, respectively.

Fig. 2. Theoretically estimated fluid pressure decline along the channel length in the presence of (a) column and (b) standard spacers at $U_F = 0.16 \text{ m/s}$ and $U_F = 0.18 \text{ m/s}$.

To validate the simulation results, the differential pressure drop inside the channel was experimentally measured using deionized water as the feed fluid (please see the differential pressure gauge (5) in the schematic diagram of the experimental set up, Fig. 1). Fig. 3(a) shows the experimentally measured pressure drop per unit length as a function of cross-flow velocity for both types of spacers. It can be seen that the differential pressure drop increases as the cross-flow velocities for both spacers are increased. Moreover, the comparison of computational and experimental values showed a good agreement for the two inlet velocities ($U_F = 0.16$ and 0.18 m/s). Within the range of this cross-flow velocities employed in this study, the maximum deviations of mean experimental results from the theoretical results were less than 6%, well within the experimental error bar. Further, the experimental differential pressure drop was also found to be roughly 6 times higher for the standard spacers as already predicted by the computational findings.

Fig. 3. (a) Comparison of experimentally measured differential pressure drop in the feed channel at various velocities and (b) error in simulation results at the operating velocities (0.16 m/s and 0.18 m/s) of this study for the standard and column feed spacers.

Fig. 4(a) and (b) show the computed streamtraces of the fluid flow path overlapped with velocity magnitude contours inside the channel with both types of spacers at $U_F = 0.16$ m/s. For the column spacer the inlet stream of the feed solution was diverged into two streams due to the obstruction introduced by the cylindrical filament nodes (Fig. 4(a)). As the node shape is cylindrical and the diameter is relatively large, it created a large vortex around the node and merged to a single stream behind the node. Furthermore, both divided streams produced a very small vortex around the filaments as the filament diameter is comparatively very small. Despite the large vortex around the node, the fluid flow remains steady as a result of the lower fluid velocity generated at the constriction zone due to the larger clearance between the spacer and the membrane. On the other hand, for the standard symmetric spacer, the inlet fluid stream was encountered by the filament intersection, dividing into two streams and the fluid travels over the filaments. For the standard spacer, the vortex around the filament intersecting node was not formed as the shape of the node is not a blunt body (Qamar et al. 2010). The larger filament diameter for the standard spacer resulted in a larger recirculation zone around the filaments. Fig. 4(c) and (d) compare the fluid streamtraces at 0.18 m/s for the column and standard spacers. At this velocity, the wake behind the nodes of the column spacer showed an oscillation on the vertical cross-sectional plane (YZ-plane) of the channel (Fig. 4 (c)). It was primarily attributed to the larger clearance between the membrane and the filament allowing the vortex perturbation behind the column base and tripping the flow to an unsteady regime at $U_F = 0.18$ m/s (Koutsou et al., 2018). It clearly indicated the onset of unsteadiness suggesting Von-Karman type of instability and shedding (Qamar et al., 2012). The smaller clearance for the standard spacer further increased the fluid velocity over the cylindrical filaments causing an enhancement in unsteadiness, and an emanation of a spiral feed flow pattern through the centre of the filament cell.

Fig. 4. Comparison of numerically simulated streamtraces superimposed with velocity magnitude for column (a, c) and standard (b, d) spacers at $U_F = 0.16 \text{ m/s}$ and $U_F = 0.18 \text{ m/s}$. Arrow heads represents the direction of fluid flow in the channel.

Fig. 5(a) and (b) describe the spatial distribution of the streamwise fluid x-velocity component at the central plane of the channel at the inlet velocity of 0.16 m/s for both spacers. Depending on the obstruction by the filaments and the nodes, the magnitude of the local fluid velocities

for both spacers changed from its inlet value. The maximum velocity at the constriction zones for the standard spacer was found almost twice as that of the column spacer. Negative velocities were mainly seen behind the nodes for both spacers. As nodes act as a support to the membrane, the fluid could flow only from the sides and not over the nodes. Therefore, in both cases minimum velocity regions were observed behind the nodes. These regions are prone to the deposition of foulant particles and termed as the dead zones.

Fig. 5. Comparison of numerically simulated x-velocity contours at the central plane of the channel for column (a, c) and standard (b, d) spacers at $U_F = 0.16$ m/s and $U_F = 0.18$ m/s. Arrow heads show the fluid flow direction.

Although these dead zones were mostly observed behind the nodes in the presence of column spacer (Fig. 5(a)), they were further extended behind the whole filaments in case of standard spacer due to the large diameter of its filaments (Fig. 5(b)). Furthermore, the increase in the feed velocity ($U_F = 0.18$ m/s) contributed to increase the inlet fluid velocity resulting in the shrink of the dead zones for both spacers as shown in Fig. 5(c) and Fig. 5(d).

Fig. 6. Spatial distribution of numerically modelled non-dimensional shear stress on the membrane surface at $U_F = 0.16$ m/s and $U_F = 0.18$ m/s) for column (a, c) and standard spacers (b, d), the blue and red colours refers to the minimum and maximum magnitudes of the shear stress respectively. Arrow heads on the figure show the direction of the flow.

Fig. 6 compares the non-dimensional wall shear stress contours on the top of the membrane surface for the column and standard spacers at two different crossflow velocities $U_F = 0.16$ and 0.18 m/s. At the low velocity ($U_F = 0.16$ m/s), the minimum and maximum shear stresses were respectively located around the nodes (dead zones) and under the filaments (constriction zones) for both spacers (Fig. 6(a, b)). As the shear stress is a function of the velocity gradient, it reached its maximal magnitude under the filaments where the velocity reached its highest

value. This maximal shear stress was estimated eight times lower in the case of a column spacer. While the highest regions of the shear stress were observed on the membrane surface along the filaments of the standard spacer (Fig. 6(b)), they were found only at two points ahead of nodes in the case of column spacer (Fig. 6(a)). When the feed velocity was raised ($U_F = 0.18$ m/s), the simulation results indicate a larger shear stress area at the same locations (Fig. 6(b, d)).

Finally, from the numerical comparison of hydrodynamics using the column spacer and the standard spacer, it can be envisaged that these two spacers have a significant difference in their hydraulic resistance. As a result of larger clearance between the filaments and the membrane surface, the column spacer causes lower pressure drop across the channel when compared to that of the standard spacer. In addition, due to the smaller clearance of the standard spacer, the local fluid velocities under the filament are high compared to the column spacer. High shear stress was observed on the membrane surface underneath the filament of the standard spacer. In contrast, the column spacer exerts relatively lower shear stress due to the less constriction in the channel. Apart from these, the potential fouling zone or dead zone for the column spacer was found only behind the nodes, but the larger dead zone was observed for the standard spacer where it was extended behind the whole filaments. The theoretical findings indicate that the hydrodynamic optimization was achieved by using the column spacer in the feed channel. Thus, the proposed spacer has the potential to reduce the specific energy consumption of the membrane-based filtration processes by reducing the pressure drop and improving flux by the reduction in fouling.

3.2. Spacer performances in the filtration system

Based on computational fundamental understanding of hydrodynamics, the energy consumption of both spacers at lab-scale filtration system was experimentally investigated at two different feed inlet velocities (0.16 m/s and 0.18 m/s). The membrane fouling effects for

these spacers were characterized by using OCT scans. Besides, the permeate flux and the average pressure drop across the flow cell were measured to determine the specific flux and the specific energy consumption.

3.2.1. Accumulation of foulants

Fig. 7 shows the two dimensional OCT images of the fouling layer developed on the membrane surface at feed velocities of 0.16 and 0.18 m/s after 48 h. At 0.16 m/s, $66 \pm 27 \mu\text{m}$ thick heterogeneous fouling layer was developed on the UF membrane in case of the standard spacer (Fig. 7(a)).

Fig. 7. OCT images of the fouling layer grown over UF membrane surface at two various crossflow velocities ($U_F = 0.16$ and 0.18 m/s) in the presence of standard (a, c), and column (b, d) spacers after 48 h of experiments.

However, at the same velocity the membrane surface appeared almost clean for the column spacer (Fig. 7(b)). At a higher feed velocity ($U_F = 0.18$ m/s), the OCT imaging results exhibited an increase in the fouling thickness to reach 132 ± 21 μm for the standard spacer (Fig. 7(c)), whereas the column spacer still performed better in terms of fouling prevention where only a loose and thin layer of foulants (28 ± 13 μm) was observed on the membrane surface (Fig. 7(d)). The column spacer has shown less fouling potential than the standard spacer as a consequence of the excessive filament obstructions in the standard design. In agreement with previous studies (Lecuyer et al., 2011; Saur et al., 2017), the highest shear stress numerically demonstrated in Section 3.1. (Fig. 6(b, d)), resulted in a high tendency of the standard spacer to seed the bacterial attachment under the filaments thereby actively promoting the growth of biofouling in the overall filtration system.

3.2.2. Impact of the column design on the filtration performance

As mentioned in Section 2.5, for each spacer the permeate flux and pressure drop directly relate to the specific flux which is used to assess filtration performance. Fig. 8 describes the specific flux decline as a function of time at two different feed inlet velocities ($U_F = 0.16$ m/s and $U_F = 0.18$ m/s) for both spacers. For the standard spacer at low velocity ($U_F = 0.16$ m/s), the specific flux decreased sharply during the first 150 min, then it continued to decrease at a slow rate to reach the steady state (average specific flux 50 LMH/bar of pressure drop) after about 2000 min (Fig. 8 (a)). Contrary, in the case of column spacer the specific flux decline rate was slower at the initial phase of the filtration (Fig. 8 (b)). The average specific flux at steady state was about two folds higher for this column design and was estimated to 101 LMH/bar. Temporal specific flux behaviors of these spacers were also studied at the higher velocity of 0.18 m/s and showed in Fig. 8(b).

Fig. 8. Experimentally measured specific flux decline with time for the filtration process at two different velocities (a) 0.16 m/s and (b) 0.18 m/s in presence of the column and standard spacers.

At this velocity, the average specific fluxes were determined to be 95 LMH/bar and 47 LMH/bar of pressure drop across the test cell in case of the standard and column spacers, respectively. The steady state specific flux of the standard spacer was compared with our previous study (Kerdi et al., 2018), where the same spacer was used with a different membrane having lower molecular cut-off (100 kDa) at 0.18 m/s feed velocity. Since the membrane was less porous, the specific flux was 38 LMH/bar of pressure drop at the same velocity. It shows that the findings of the current study are in a very good agreement with the previous study. In conclusion, the column design spacer type achieves relatively lower fouling surface on the membrane (Fig. 7 (b, d)) and, therefore, performs better than the standard spacer in terms of specific flux.

Fig. 9 compares all the major performance parameters including the specific flux, the average pressure drop and the specific energy consumption of the filtration system for experiments conducted at two inlet velocities 0.16 m/s and 0.18 m/s. At the low velocity, Fig. 9(a) shows that the column design led to an average pressure drop (across the filtration channel) three times lower than the standard design, where the values were monitored to be 62 and 186 mbar, respectively. Average pressure drop was calculated by determining the mean value of the initial pressure drop and the final pressure drop for the experiments. This lower pressure drop in case of column spacer was predicted due to the high clearance designed between the membrane and the spacer thereby the lower hydraulic resistance applied inside the flow cell. Furthermore, the use of less material in the novel design resulted in lower pressure drop (Siddiqui et al., 2017) as it increased the channel porosity (porosity of the standard spacer and column spacer are 0.7 and 0.85 respectively).

Fig.9. Comparison of the experimentally measured filtration performances for the column and standard spacer in a lab-scale filtration process at two different velocities (a) 0.16 m/s and (b) 0.18 m/s.

Therefore, due to the direct proportional relationship between the pressure drop and the SEC of the filtration system (Section 2.5), the overall filtration system consumed less specific energy for the column spacer (1 kWh/m^3) as compared to the standard spacer (2 kWh/m^3). It is worth mentioning here that for calculation of SEC, the final steady-state flux and pressure drop were considered. When the velocity was increased to 0.18 m/s , the column spacer still performed better than the standard spacer in terms of specific flux (95 LMH/bar pressure drop at steady state), average pressure drop (81 mbar) and energy consumption (1.5 kWh/m^3) (Fig. 9 (b)). It is important to point out that a lower specific flux of 95 LMH/bar was observed at a higher velocity of 0.18 m/s compared to the velocity of 0.16 m/s , which was found to be 101 LMH/bar of pressure drop. The rise in the pressure drop can explain this slight reduction in the specific flux and the fouling effect where a thin cake layer was visualized through OCT scans on UF membrane surface at the high velocity of 0.18 m/s contrarily to 0.16 m/s (Section 3.2.1-Fig. 7 (b, d)). The experimentally measured SEC values of the lab-scale UF setup in this study were quite high as compared to a full scale UF system (Glucina et al., 1998; Pearce, 2008). This high energy consumption is attributed to the very small membrane area of the flow cell and the filtration operation at very low transmembrane pressure. However, these values were only used to compare the performances of the spacers when the same operating conditions were maintained for the both spacers.

4. Conclusions

A novel column type spacer was developed in this study to reduce the energy consumption of the membrane-based filtration processes by optimizing the hydrodynamics of the spacer filled channel. 3D CFD simulation was carried out to compare the fluid flow behaviors in the channel at two different feed solution inlet velocities for the proposed spacer and a standard symmetric

spacer. To support the theoretical findings, filtration performances of both spacers were experimentally investigated. The main findings of this study are listed below:

- CFD simulation showed substantial pressure drop reduction for the column spacer as compared to the standard spacer. It also reduced the shear stress at the constriction zone. Moreover, the dead zone was also shortened for the proposed column spacer.
- Specific flux for the column spacer was found twice as high as that for the standard spacer. At 0.16 m/s and 0.18 m/s feed solution velocity, the specific fluxes for the column spacer were 101 LMH/bar and 95 LMH/bar, whereas the specific fluxes for the standard spacer at these velocities were 50 and 47 LMH/bar of pressure drop across the test cell respectively. About two folds reduction in specific energy consumption was observed for the column spacer as compared to the standard spacer at both velocities.
- Three times lower pressure drop was found for the column spacer as compared to the standard spacer when a synthetic feed solution of very high fouling potential was used at 0.16 and 0.18 m/s.
- OCT scans indicate much lower biofilm accumulation on the membrane surface for the column spacer. At both 0.16 and 0.18 m/s velocity, the proposed column spacer design produced cleaner surface.

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