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Hydrodynamics of sinusoidal spacers for improved reverse osmosis performance

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ABSTRACT

A key to maximizing flux and decreasing fouling in reverse osmosis (RO) is to decrease concentration polarization. This is currently partially accomplished by mesh feed spacers, but mesh spacers increase the longitudinal pressure drop and form dead zones where foulants accumulate. Alternative spacer geometry is presented here where sinusoidal flow patterns are created. Several models of RO spacer channels with varying amplitude and wavelength in their sinusoids were created for evaluation by three-dimensional computational fluid dynamics (CFD) simulations (COMSOL Multiphysics software) that included predictions of concentration polarization and flux. Results over a range of pressures and salt concentrations indicated that the more tortuous geometries (higher amplitude and shorter wavelength) induced greater local fluid velocity and decreased concentration polarization, which led to greater flux. Taylor–Goertler vortices generated in the peaks and valleys of the channels aided in mass transfer. The drawback to the sinusoidal geometry was an increased pressure drop, but one of the sinusoidal geometries tested had both a lower pressure drop and higher flux than a conventional mesh spacer. A subset of the spacer geometries was built and tested experimentally in a bench-scale RO unit. Experimental and modeling data were in good agreement, confirming the benefits of the sinusoidal spacer geometries and suggesting that CFD is an effective tool for predicting performance.

1. Introduction

Reverse osmosis (RO) is widely used for producing high purity water because of its ability to reject most dissolved and suspended materials [1,2]. Spacers are used in the membrane module to separate the membrane sheets and form flow channels. Spacers are also designed to reduce concentration polarization, which is the key problem in most RO membrane systems [3,4]. Concentration polarization diminishes the permeate quality, decreases flux, and can result in membrane fouling via precipitation and cake formation on the membrane surface. Spacers reduce concentration polarization by increasing the local fluid velocity and shear rate, thus enhancing the mass transfer of salts away from the membrane surface [5]. The mesh geometry spacer is the most common type used in currently marketed spiral-wound RO modules [6].

The main problem associated with mesh spacers is that even though they can decrease concentration polarization, their method of disrupting flow between membrane leaves creates areas of stagnant flow, or dead zones, and entrapment sites where foulants can accumulate [7]. Investigations of membrane fouling commonly show that spacers play a key role in the fouling process and fouling often occurs in a pattern defined by the mesh spacer [8,9]. Barker et al. [10] and Tran et al. [11] reported that fouling initially started along the feed spacer and then gradually encroached upon the rest of the clean membrane area. Vrouwenvelder et al. [9] and Paassen et al. [12] independently studied the correlation between spacers and biofouling. They reported that biofouling was largely initiated on feed spacers and the pressure drop caused by biomass accumulation was much higher when the spacer was present. Overall a consensus is emerging that spacer design is a critical element in addressing fouling problems and in designing new RO modules. While a great deal of work in recent years has focused on membrane surface modification to make anti-fouling or foulant-resistant membranes [9,13,14], the benefits of those surface modifications may be diminished if spacer design is not addressed.

Several efforts toward improving upon the conventional mesh spacer have been made, with the goal of inventing a spacer that can promote permeate flux but reduce fouling [15–18]. The drawback to novel spacers is that their success at mitigating concentration polarization and improving flux comes at the cost of higher energy consumption; spacers disrupt the flow path, increasing the hydrodynamic resistance and longitudinal pressure drop [16,17,19–22]. For example, Schwinge et al. [18] tested a three-layer mesh spacer that had higher flux when compared to the traditional two-layer spacer, but it incurred higher pressure drop [18]. Schwinge and Wiley [7] investigated the performance of a zigzag spacer in a spiral-wound

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module and saw that pressure drop was lower than with a mesh spacer, but the permeate flux was also reduced. The challenge of creating a spacer that reduces concentration polarization at the same or lower pressure drop as the conventional mesh spacer remains elusive, and is the goal of the present work.

In designing novel spacers, two general approaches are taken: experimental and computational. Early experimental work investigated the mass transfer and pressure drop characteristics caused by different kinds of mesh spacers and found that performance was influenced by parameters like spacer thickness, material, porosity, orientation and hydraulic diameter [19,20]; however, it is extremely difficult to observe and quantify how these parameters affect flow hydrodynamics in experiments. Such knowledge is critical in understanding the mechanisms with which the spacers influence the performance of the membrane.

With the advent of computational fluid dynamics (CFD) tools, other studies have taken a closer look by simulating the flow and mass transfer inside the membrane channel [2,17,18,21–28]. Two-dimensional (2D) CFD studies are most common because they are less computationally demanding than three-dimensional (3D) efforts. 2D studies have examined the effect of spacer geometry, such as the cavity, submerged, and zigzag types on membrane filtration performance [7,21–23,25]. Those studies provide valuable insights into pressure, flow and concentration inside the membrane channel and prove that parameters like spacer filament spacing, thickness and cross-sectional geometry are important in reducing concentration polarization.

Even though 2D simulation is useful in investigating flow dynamics and mass transfer [29], the flow in membrane filtration is 3D by nature because of the feed spacer. Improvements in computer speed and numerical efficiency in CFD codes have made 3D simulations of spacer geometries practical. Iwatsu et al. [30] reported that simulations of flow velocity varied significantly between 2D and 3D models at Reynolds number over 800. In addition, mass transfer was reported to be higher in 3D models than 2D [31]. The 3D simulation enabled researchers to examine the effects of flow angle and filament angle in woven and non-woven filaments [6,16,24,31].

In the present study we have combined both computational and experimental approaches to demonstrate the utility of a novel spacer with sinusoidal geometry. Sinusoidal channels have been used in apparatuses like heat exchangers to achieve considerable mass and heat transfer enhancement at low pressure drop [32,33]. Nishimura et al. [34–36] performed a series of experiments regarding flow characteristics and mass transfer in sinusoidal wavy channels, where the channels were able to generate vortices both in transverse and longitudinal directions; e.g. 3D flow. The vortices disrupted the flow pattern, thus increasing mass transfer. Here we show that sinusoidal flow can similarly enhance mass transfer in RO, increasing flux with the same or lower energy requirements as conventional mesh spacers. To our knowledge the use of sinusoidal channels in RO applications has not yet been reported.

2. Materials and methods

2.1. Model description

Five models of RO spacer channels with varying geometry were created for analysis (Fig. 1). The channels included four sinusoidal patterns with wall geometry described by

$$y = a\ \sin\left(\frac{2\pi x}{L}\right) \tag{1}$$

where a is the amplitude and L is the wavelength. a was either 3 or 6 mm, and L was either 12 or 24 mm. The cross-sectional geometry

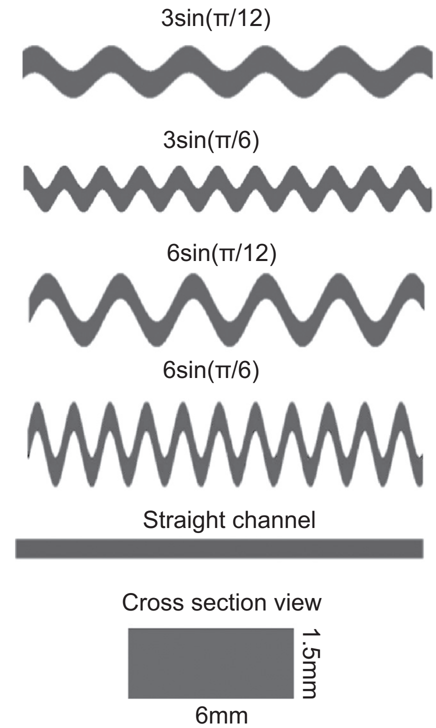

Fig. 1. Geometries of sinusoidal channels. The overall length of each channel is 130 mm. The cross-sectional view (bottom) applies to all geometries.

of the channel was a 1.5 mm by 6 mm rectangle, with the membrane lying along one of the 6 mm sides. A straight channel was also modeled, representing the non-sinusoidal control. The channel geometries will be referred to as *3sin*($\pi/12$), *3sin*($\pi/6$), *6sin* ($\pi/12$), *6sin*($\pi/6$), and straight channel.

A conventional mesh spacer was also simulated. The mesh spacer channel had the same dimensions as the straight channel except that it was filled with a mesh spacer with the geometry of the filaments used in experiments. Due to the complexity of the flow field induced by the mesh spacer, the mesh spacer model (unlike the sinusoidal models) neglected the permeate through the membrane, which was less than 0.6% of the cross-flow rate; the mesh spacer model was only used to simulate the pressure gradient.

Models were created and solved using Comsol Multiphysics 4.2a. This code used the Galerkin finite element method to solve governing equations over a computational mesh. The mesh consisted of tetrahedral elements through the subdomain, with thin rectangular elements at the boundaries. Mesh density was evaluated by comparing results from different meshes. For example, the flux for sinusoidal channel *6sin*($\pi/6$) with 783,230 elements differed less than 0.9% from the flux with a mesh density that was 12% greater (894,880 elements). This small change in the result ($<1\%$) with a 12% change in mesh density was acceptable, so the mesh with fewer elements was used to decrease the computational intensity. The mesh densities for straight, *3sin*($\pi/12$), *3sin*($\pi/6$), *6sin*($\pi/12$), *and 6sin*($\pi/6$) were 510, 458, 470, 533 and 644 elements per mm^3 and the volume for each channel was 1200 mm^3.

Fluid flow and transport of sodium chloride (the only solute) inside the channel was described by Eqs. (2)–(4),

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

$$\rho \mathbf{u} \nabla \cdot \mathbf{u} = \nabla \cdot [-P + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T] \tag{3}$$