Computational fluid dynamic analysis of RO membrane performance with novel feed spacer geometries

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ABSTRACT

A finite element based numerical model has been employed to describe momentum and mass transfer in open and spacer-filled crossflow membrane channels. Simulations considering operating conditions typical of seawater (SW), brackish water (BW), and reuse water (RW) reverse osmosis (RO) applications are employed for optimization of hypothetical spiral wound element feed spacer designs. Preliminary results suggest that for lower TDS waters, energy consumption is minimized at smaller spacer-to-channel height ratios. Conversely, larger spacer-to-channel thickness ratios result in minimal energy consumption when processing higher TDS waters. Spacer shape has little impact on concentration polarization (CP), but spacer shape has a large effect on axial pressure losses. A variety of spacer shapes and designs are simulated and evaluated for each water source.

INTRODUCTION

Concentration polarization is an important factor that limits separation performance in nearly all crossflow membrane filtration processes (Mulder, 1991). For example, polarization of rejected solutes in reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) separations causes elevated concentrations at the membrane-solution interface, which increases solute passage and trans-membrane osmotic pressure. In addition, CP exacerbates all forms of surface fouling phenomena including scale formation by sparingly soluble mineral salts, cake formation by colloids, gel formation by organics, and biofilm formation by bacteria. Therefore, accurate description of CP phenomena is critical for design, optimization, and operation of RO membrane separations.

MATERIALS AND METHODS

A previously developed finite element model has been applied to study momentum and mass transfer in crossflow membrane filtration systems with open and spacer-filled channels (Subramani et al., 2006). A commercially-available finite element solver (FEMLAB 3.0, © COMSOL AB), was used to construct the model geometries and perform numerical simulations. The model employs the steady-state Navier-Stokes, continuity, and convection-diffusion equations as shown in eq (1-3), respectively.

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} + \frac{1}{3}\mu \nabla\left(\nabla \cdot \mathbf{v}\right) \tag{1}$$

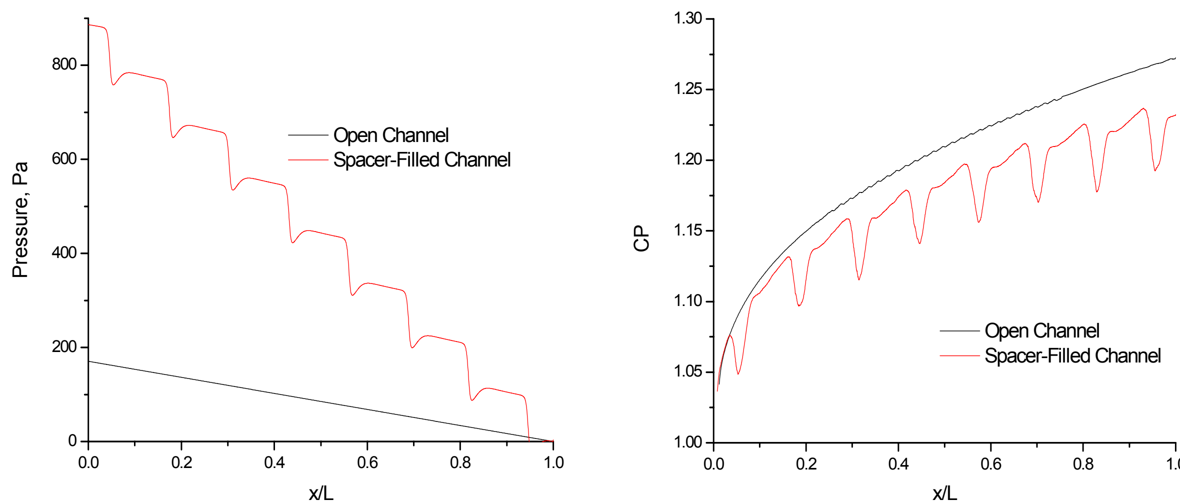
$$\nabla \cdot \mathbf{v} = 0 \tag{2}$$

$$\frac{\partial c}{\partial t} = -\nabla \cdot \left(-\mathbf{D} \cdot \nabla c + \mathbf{v}c + \frac{\mathbf{D} \cdot \mathbf{F}}{kT} c \right) \tag{3}$$

Simulation conditions represent practical reverse osmosis operating conditions and membrane properties considering both open and spacer-filled channels. Although the model is two-dimensional and somewhat simplified, the results provide valuable insight to guide further exploration in feed spacer design and optimization. Optimal spacer design will be evaluated based on mass and momentum transport. The design which results in the lowest axial and osmotic pressure losses is deemed the optimal spacer design for the given operating conditions.

RESULTS AND DISCUSSION

In straight-through open channels, finite element numerical model results agree reasonably well with classical analytical models for predicting pressure drop and wall shear rate, but differ from the film theory-based concentration polarization model for most combinations of crossflow and permeate hydrodynamics (Subramani et al., 2006). In spacer-filled channels, axial frictional pressure losses are always higher than in open channels, whereas concentration polarization is (on average) reduced for all spacer geometries considered as shown in Figure 1. Figure 2 shows preliminary results which suggest that certain spacer geometries create zones where fluid mixing stagnates near the membrane surface. This leads to "spacer-enhanced concentration polarization," which (theoretically) could promote localized scale, cake, gel, and biofilm formation. As a result, we have begun exploring novel feed spacer geometries that may lead to improved spacer designs for practical membrane modules. Results from these and other simulations of fluid flow, pressure drop, concentration polarization, and particle transport can help to describe the efficacy of a given feed spacer geometry.



(a) **(b)**

Figure 1. Comparison of (a) axial pressure losses and (b) concentration polarization in open and spacer-filled channels.

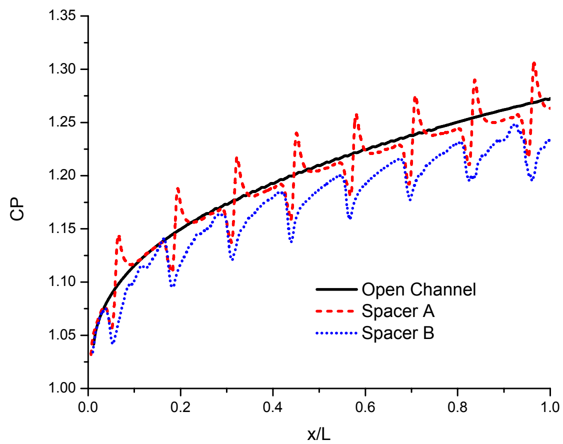


Figure 2. Evidence of spacer-induced stagnation zones as shown by Spacer A. Spacer B shows a consistent reduction of CP.

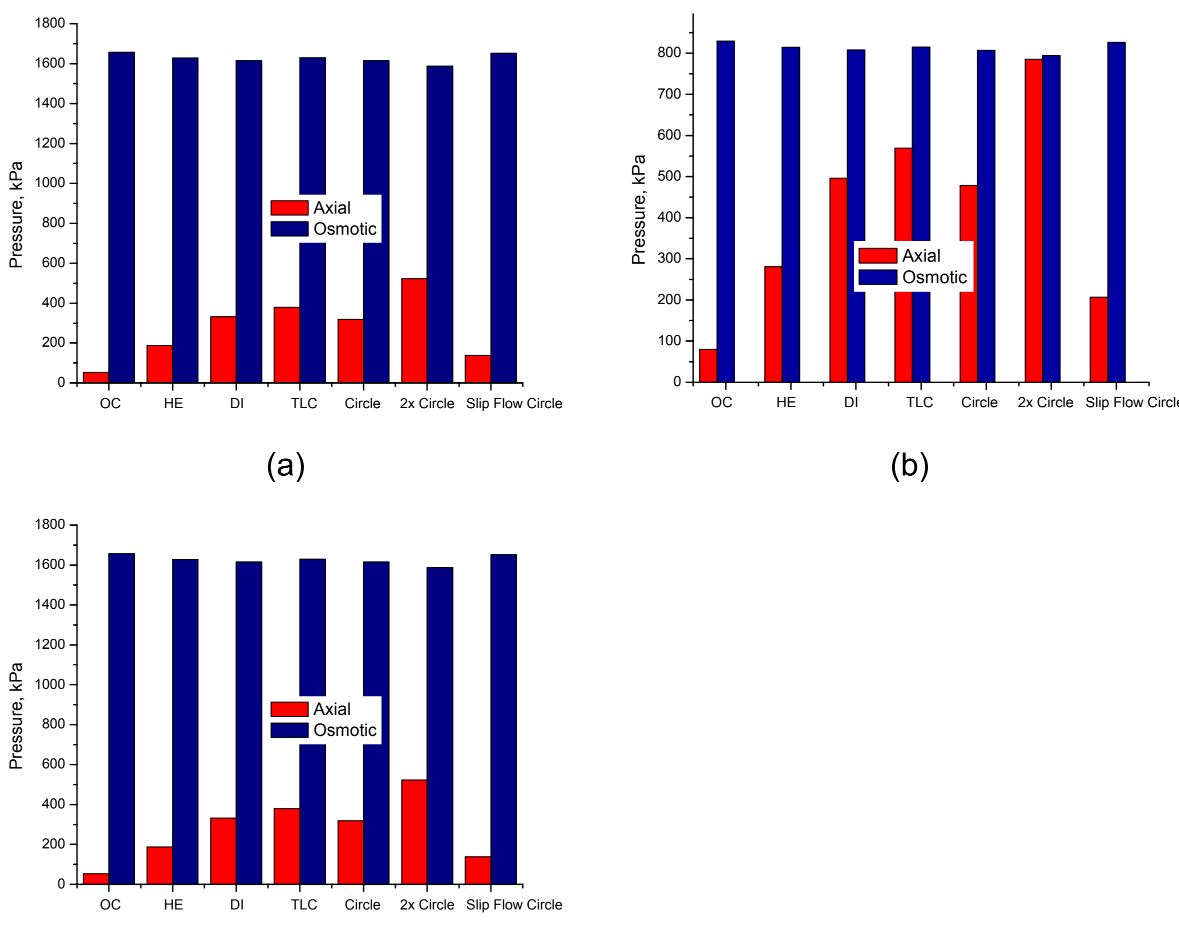


Figure 3. Breakdown of axial and osmotic pressure losses for (a) SWRO, (b) RWRO, and (c) BWRO applications using various spacer shapes and designs.

The results of these simulations suggest that the influence of concentration polarization on trans-membrane osmotic pressure is the main source of energy loss in SWRO applications (Figure 3(a)), while axial frictional losses cause the greatest proportion of energy loss in RWRO applications (Figure 3(b)). In BWRO applications (Figure 3(c)), the balance of frictional and osmotic pressure losses are dependent on feed water osmotic pressure, membrane properties, and operating conditions.

CONCLUSIONS

A finite element method based model was constructed to describe mass and momentum transport in straight-through open channel and spacer-filled membrane channels. Simulation results suggest that optimizing spacer size based on feed water quality is crucial for reduction of energy consumption. Spacer shape has some effect on mass transfer, but non-spherical shapes produce large pressure losses. Reducing CP any further may yield diminishing returns in terms of osmotic pressure losses. However, reducing CP may have greater significance in the reduction of scaling and fouling potential. Next generation feed spacer design should make use of electro-kinetic and interfacial phenomena because hydrodynamically reducing CP is far too costly.

ACKNOWLEDGMENTS

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