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A study of flow field and concentration polarization evolution in membrane channels with two-dimensional spacers during water desalination

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ABSTRACT

This study is a step toward *integrated* modeling of the evolving (in space and time) flow and concentration fields during water desalination in membrane spacer-filled channels. Such detailed model predictions are of practical significance, leading to improved understanding of spiral wound membrane (SWM) module operation. *Submerged* and *zigzag* spacer filament 2-dimentional configurations are employed, as they create geometric flow-channel features (contact lines, flow constrictions, etc) encountered in SWM modules. The numerical study, performed in a Reynolds number range typical for desalination modules, is focused on the evolution of local mass transfer coefficient k and concentration polarization, which significantly affect SWM module performance. A detailed quantitative prediction is obtained of these parameters, which are linked to the variation of wall shear stress, static pressure and permeation flux. By focusing on a typical region of the membrane channel (adequately capturing the evolving flow characteristics), it is predicted that increasing average k values (with the concomitant reduction of concentration polarization) are associated with the undesirable increase of pressure drop; these conflicting requirements can be balanced through the selection of appropriate spacer geometry. The negative effect of membrane-filament contact lines on concentration polarization is well documented. An assessment is made of the two spacer filament configurations, from this perspective, and directions for future research are outlined.

1. Introduction

In recent years the volume of produced desalinated seawater, using the method of purification by Reverse Osmosis (RO) membranes, has significantly increased. Therefore, particular efforts have been devoted to the optimization of spiral wound membrane (SWM) modules [1], which represent the essential unit-equipment of the process. In addition to the experimental work, CFD is a highly efficient and inexpensive tool for studying the phenomena of mass transfer inside functioning SWM modules and the corresponding bibliography is extensive. Reviews on this subject can be found in relatively recent references (e.g. [2,3]). Classification of currently used models may be made [4] either on the basis of the length scales involved in SWM module operation or according to their time dependence. Regarding the former category, models of membrane-module operation at various scales have been proposed in investigations of species concentration distribution at the concentrate-side [5–10] or at both sides of the membrane [11–13].

The unavoidable use of spacers between membranes, that create flow unsteadiness and enhance fluid mixing, is a convenient means for improving the performance of spiral wound membrane (SWM) modules. Schwinge et al. [14–17] have contributed to the understanding of the hydrodynamics and the mass transfer phenomena, through numerical studies with different configurations (referred to as *cavity, zigzag, attached*). Simulations were performed for a single type of spacer configuration with several geometric parameters [14]. In other publications, these authors investigated the effect of shear stress and pressure drop on the mass transfer coefficient [15] and then extended their study for unsteady flows [16,17]. In parallel, Cao et al. [18] considered an unsteady and turbulent flow; their results showed the significant influence of obstacles on the shear stress near the membrane which tends to improve the mass transfer coefficient.

Geraldes and collaborators treated a rectangular feed channel of nanofiltration (NF) membranes filled with *ladder-type spacers*,

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and analysed the hydrodynamic field [19] as well as concentration polarization [20,21]. Later Koutsou et al. [22], using Direct Numerical Simulation (DNS), studied the case of a plane narrow channel with a periodic array of cylindrical obstacles with their axes placed on the mid-plane of symmetry. Their modelling approach allows the reduction of the computational load by imposing periodic boundary conditions between successive cylindrical filaments, thus reducing the computational domain to one unit cell. The aim was to study the detailed flow characteristics and the effect of the spacer filaments on the flow field. However, in this model system, mass transfer was not considered and the salt concentration distribution near the membrane surface was not determined.

Improving the performance of SWM modules by varying the geometry of the spacer-filaments has been the subject of several studies [23–25], although some of these alternative geometries did not appear to be as effective as the conventional spacer form [23]. However, in another study, Dendukuri et al. [25], using different concave shapes with a variable geometric ratio, have found (among other interesting results) that these new forms can reduce the pressure drop compared to the conventional form. In parallel, the impact of different configurations and of the spacing between square obstacles/filaments was studied by Ma et al. [26,27] using the Petrov/Galerkin method for solving the conservation of momentum and mass equations. These studies suggested that the *zigzag* configuration tends to reduce the concentration polarization and to improve the permeation flux. A short section of an open channel with different configurations of spacers was also simulated by Subramani et al. [28]; although concentration polarization phenomena and pressure drop were treated, only one membrane in the channel was taken into consideration. Later, Wardeh and Morvan [29] performed CFD simulations for a spacer-filled channel bounded by two membranes; interesting results were obtained, but the numerical model [29] did not include temporal evolution of the phenomena involved and appeared to entail a significant computational load. It is also worth noting that some other significant numerical investigations were conducted by Wardeh and Morvan [30] and Li et al. [31–33], concerning the effect of curvature (of membrane channels with spacers encountered in the cylindrical SWM modules) on the hydrodynamics and mass transfer.

In summary, previous studies deal with various spacer configurations (*submerged*, *zig-zag*, *ladder-type*) and their effect on the development of the flow field and on key process parameters like pressure drop [14,17,18,28,29,34], shear stress [18,22,29,35], mass transfer coefficient [8,15,34,35,37], while concentration polarization is studied either in steady state modes [9,10,20,21,26,29] or neglecting the permeation along the membranes [8]. The novelty of this work lies in the fact that it deals with the spatial development and evolution of concentration distribution (and of the related boundary layer) in spacer-filled channels by taking into account the time-varying behavior of the flow field in these systems. In this study by taking into account, for the first time, the fluid permeation through both membranes (comprising the channel), the concentration distribution (i.e. the concentration polarization) along the membrane surfaces is calculated. The study takes into consideration the time-dependent nature of the phenomena involved by integrating the instantaneous results over sufficient periods of the time-varying (oscillating) parameters. The local mass transfer coefficient along the membranes is calculated for the *submerged* and *zigzag* configurations and special attention is paid to link its evolution to several pertinent parameters such as shear stress, permeation flux and static pressure. Finally, the salient features of the evolving concentration field and of the related boundary layer at the membrane surfaces are visualized in fair detail and interpreted.

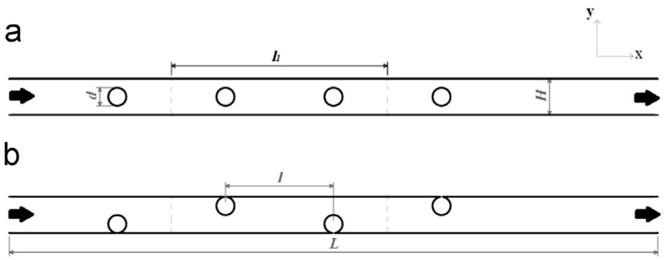

Fig. 1. Geometrical arrangement of transverse cylindrical filaments: (a) *submerged*, (b) *zigzag.*

2. Problem formulation and numerical method

The computational domain is shown in Fig. 1. The physical model of 2D narrow horizontal channel, filled with spacers for the *submerged* configuration (Fig. 1a) and the *zigzag* configuration (Fig. 1b), consists of two parallel plates representing membrane walls at a distance $H=2$ mm. The channel length ($L=36$ mm) and the spacer filament diameter (d) are chosen so that $(d/H)=0.5$. The distance between two neighboring filaments is three times the channel height; i.e. $l=3$ H. A sufficient entrance length is employed to ensure a fully developed flow and a long exit length is chosen to avoid the outlet interference with the recirculation region formed downstream of the last filament [29].

The numerical model for fluid flow and mass transfer within these channels was developed under some assumptions including two-dimensional (x, y), time dependent, isothermal, laminar flow and an incompressible Newtonian fluid; the latter is an aqueous solution of NaCl. Gravity, viscous dissipation and compressibility effects are neglected. Under these assumptions, the equations of continuity, momentum and mass transfer are cast in their dimensionless form as follows:

$$\frac{\partial\rho}{\partial t}+\nabla.\ (\rho\boldsymbol{U})=0 \tag{1}$$

$$\frac{\partial\rho\boldsymbol{U}}{\partial t}+\nabla.(\rho\boldsymbol{U}\boldsymbol{U})=-\nabla.\left[\mu\left(\nabla\boldsymbol{U}+\nabla\boldsymbol{U}^{T}\right)\right]-\nabla P \tag{2}$$

$$\frac{\partial\rho m_A}{\partial t}+\nabla.(\rho\boldsymbol{U}m_A)=\nabla.(\rho D_{AB}\nabla m_A) \tag{3}$$

In Eqs. ((1)–(3)) ρ, $\boldsymbol{U}$, μ, and P are the density, velocity, dynamic viscosity, and static pressure while m_A and D_{AB} are the salt mass fraction and the binary diffusion coefficient of the solute A in the solvent B, respectively.

A solution of pure water and solute (sodium chloride) flows into the feed channels for all simulations. The physical properties (in S.I.) of the aqueous solution vary depending on the salt mass fraction according to Eqs. (4)–(7) as described by Geraldes et al. [6] for a mass fraction not exceeding 0.09 kg/kg.

$$\pi=805.1\times10^{5}\ m_A \tag{4}$$

$$\mu=0.89\times10^{-3}(1+1.63m_A) \tag{5}$$

$$D_{AB}=\ \max(1.61\times10^{-9}(1-14m_A),1.45\times10^{-9}) \tag{6}$$

$$\rho=997.1\times(1.0+0.696m_A) \tag{7}$$

Initially, at $t=0$, a constant velocity (u_0) and solute mass fraction (m_{A0}) are applied at the inlet. At the outlet, an open boundary condition is assumed. At the impermeable filament surfaces no slip and no solute flux conditions are imposed. On the membrane walls, there is no slip velocity ($u=0$) with the normal component v expressed as a linear function of the trans-membrane pressure (ΔP)