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Experimental and numerical characterization of the water flow in spacer-filled channels of spiral-wound membranes

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ABSTRACT

Micro-scale flow distribution in spacer-filled flow channels of spiral-wound membrane modules was determined with a particle image velocimetry system (PIV), aiming to elucidate the flow behaviour in spacer-filled flow channels. Two-dimensional water velocity fields were measured in a flow cell (representing the feed spacer-filled flow channel of a spiral wound reverse osmosis membrane module without permeate production) at several planes throughout the channel height. At linear flow velocities (volumetric flow rate per cross-section of the flow channel considering the channel porosity, also described as crossflow velocities) used in practice (0.074 and 0.163 $m \cdot s^{-1}$) the recorded flow was laminar with only slight unsteadiness in the upper velocity limit. At higher linear flow velocity (0.3 $m \cdot s^{-1}$) the flow was observed to be unsteady and with recirculation zones. Measurements made at different locations in the flow cell exhibited very similar flow patterns within all feed spacer mesh elements, thus revealing the same hydrodynamic conditions along the length of the flow channel. Three-dimensional (3-D) computational fluid dynamics simulations were performed using the same geometries and flow parameters as the experiments, based on steady laminar flow assumption. The numerical results were in good agreement (0.85–0.95 Bray–Curtis similarity) with the measured flow fields at linear velocities of 0.074 and 0.163 $m \cdot s^{-1}$, thus supporting the use of model-based studies in the optimization of feed spacer geometries and operational conditions of spiral wound membrane systems.

1. Introduction

Membrane filtration processes for seawater desalination and wastewater reuse are becoming increasingly important. In a spiral-wound membrane module, most commonly used in these water treatment processes, the membrane sheets are rolled around an inner tube. To keep the membrane leafs apart a relatively thin spacer net is inserted. The feed spacer promotes flow instabilities to enhance mass transfer and reduce concentration polarization (Fimbres-Weihs et al., 2006; Gao et al., 2013). However, aside from a beneficial impact, the feed spacer also contributes to pressure drop increase along the flow channel. Furthermore, a major drawback in membrane technology is fouling, i.e. accumulation of unwanted material on the membrane and spacer surface (Antony et al., 2011; Baker and Dudley, 1998; Flemming, 2002; Ridgway et al., 1983; Salvador Cob et al., 2012). Micro-sized particles, colloids, organic macromolecules can deposit and microbial cells can attach, grow and form biofilms on the membrane and spacer surfaces and decrease the filtration performance (Flemming, 1997; Tang et al., 2011; Yiantsios and Karabelas, 2003). Baker and Dudley (1998) reported that initial deposition of fouling occurred on the feed spacer filaments and on the membrane alongside the spacer and,

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with time, intruded upon the remaining free membrane area.

It was shown that fouling accumulation can be controlled to some degree by suitable hydrodynamic conditions (Sablani et al., 2001). Moreover, the same amount of accumulated fouling material can have a different impact on performance, depending on the hydrodynamic conditions (Araújo et al., 2012; Bucs et al., 2014; Valladares Linares et al., 2014; Vrouwenvelder et al., 2011). Feed spacer geometry and operational conditions (e.g., flow velocity, transmembrane pressure, etc.) have a profound influence on the flow pattern and foulant deposition in spacer-filled channels (Radu et al., 2014; Vrouwenvelder et al., 2009). To design new spacers with the least pressure drop, minimal fouling propensity, and maximum mass transfer, it is therefore important to both be able to determine experimentally and to numerically calculate the hydrodynamics (i.e., velocity and pressure profiles, shear at the walls, etc.) in these flow channels.

The impact of different spacer geometries on the flow pattern is not easily measurable experimentally due to the inherently small length-scales involved. Alternatively, advances in numerical performance have led to computational fluid dynamics (CFD) techniques being the primary means to understand the fluid flow in spacer-filled channels. Some studies have simulated fluid flow and mass transfer in simplified two-dimensional setups (Schwinge et al., 2002; Radu et al., 2010). However, in recent years, three-dimensional (3-D) numerical models are becoming increasingly accessible, developed mainly with an emphasis on the effect of feed spacer on hydrodynamics and mass transfer in feed spacer channels (Koutsou et al., 2007, 2009; Saeed et al., 2012). Simplified cylindrical shapes have been used for representation of spacer filaments in most of the numerical studies. However, microscopic observations of the feed spacer revealed that the spacers used in commercially available spiral-wound membrane modules have more irregular geometry, with filaments varying in thickness (Fimbres-Weihs and Wiley, 2010; Picioreanu et al., 2009; Vrouwenvelder et al., 2010). Simulations by Picioreanu et al. (2009) showed that the feed channel pressure drop for a simplified spacer with cylindrical filaments is significantly different from more realistic spacer geometry with variations in filament thickness. The importance of realistic spacer geometries in numerical studies was also revealed by a recent experimental and numerical study on particle deposition in spacer channels at various feed spacer orientations (Radu et al., 2014).

In contrast with the abundance of numerical studies, only a few experimental investigations were carried out to directly visualize and characterize the flow patterns in feed spacer-filled channels. This may be partly due to the geometrical complexity and small dimensions of the flow channels (thereby the need for microscopic techniques), but also due to the high temporal resolution required (i.e., very fast flows require use of fast cameras).

Nuclear magnetic resonance (NMR) or magnetic resonance imaging (MRI) has been used to locally resolve (in 3-D) the velocity and shear stress distribution in tube reactors containing biofilms (Manz et al., 2003; Wagner et al., 2010). In spacer-filled channels with and without biofilm, NMR was used to visualize and measure two-dimensional velocity profiles (Vrouwenvelder et al., 2010). Formation of preferential flow patterns was observed as biofouling evolved in time. However, as a limitation of the method used, the flow cell was operated with 10 times lower linear flow velocity than normally used in practice, and the measured velocity had to be averaged over the flow channel height.

Doppler optical coherence tomography (DOCT) was also used to measure and visualize the local velocity profile in a spacer-filled channel (Gao et al., 2013). The DOCT could reveal the flow profile normal to the main flow direction at different sections along the flow channel. Furthermore, the development of eddies were observed next to the spacer filaments.

Particle image velocimetry (PIV) was used to characterize the flow next to the membrane surface at different linear flow velocities by Gimmelshtein and Semiat (2005) and Willems et al. (2010). Gimmelshtein and Semiat (2005) found laminar flow at commonly used linear flow velocities (0.06–0.17 $m \cdot s^{-1}$), with (expectedly) increasing mixing intensity at higher linear flow velocities. The measured flow fields were in good agreement with the two-dimensional numerical simulations developed by the authors (Gimmelshtein and Semiat, 2005). Willems et al. (2010) used PIV techniques to achieve a quantitative description of the two-phase flow in spacer-filled channel. Although the temporal resolution was low, the study showed how the flow direction changed along the channel height and also evaluated the impact of bubbly flow on local velocity. PIV techniques were also applied to investigate the flow patterns in flow channels using modified saw-tooth spacer geometries (Liu et al., 2015). However, the flow channel thickness (4 mm) in these experiments was much higher than in reverse osmosis/nanofiltration systems applied in practice.

In summary, all of these experimental methods have some limitations in terms of the flow channel thicknesses used, the applied linear flow velocity, the spatial or temporal resolution. As such, the objectives of this study were: (i) to evaluate the micro-scale flow patterns in a feed spacer-filled channel under conditions representative for current practical applications (i.e., similar linear flow velocity and channel dimensions) using a PIV system, and (ii) to compare the measured flow fields with three-dimensional numerical simulations.

2. Materials and methods

2.1. Experimental

Micro-scale fluid flow patterns in spacer-filled channels were experimentally investigated by particle image velocimetry (PIV).

2.1.1. Flow cell

For PIV measurements, a fully transparent flow cell was constructed from two high quality glass slides (2.5 cm width and 7.5 cm length, VWR International, West Chester, PA) (Fig. 1). Commercially available non-woven Toray feed spacer with 31 mil (0.787 mm) thickness was inserted between the glass slides. The height of the flow cell was adjusted to fit the feed spacer thickness and to avoid bypass flow below or above the spacer, then the whole ensemble was glued with epoxy resin on the sides. Water connectors were fabricated from nylon tubing with 4 mm (for inlet) and 6 mm (for outlet) inner diameter (Fig. 1).

In order to keep the flow cell transparent, no membrane sheets were inserted into the flow channel and the flow cell was operated without permeate production. The impact of permeation on the cross flow velocity in our lab scale flow cell (7.5 cm long) is negligible since the permeate velocity typically in the order of 10 $\mu m \cdot s^{-1}$, (Radu et al., 2010) is four orders of magnitude lower than the linear flow velocity of the feed water (in the order of 10 $cm \cdot s^{-1}$). Even without permeation, the presence of a membrane sheet instead of glass wall would not visibly influence the flow pattern, because the average roughness of an RO membrane is in the order of 50 nm (Ishigami et al., 2012), three orders of magnitude lower than our depth of field for flow visualization in z direction.

To eliminate pulsations generated by pumps, hydrostatic pressure was used instead to drive the water flow through the flow cell. A 3 L reservoir was placed about 1 m above the flow cell and connected to the flow cell inlet. The flow rate was adjusted with a valve connected to the flow cell outlet. To maintain constant flow rate the water level was kept constant in the reservoir by