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Characteristics of permeate-side spacers of spiral wound membrane modules

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HIGHLIGHTS

- Methodology for accurate determination of permeate-side spacer permeability.
- Typical effective lateral permeabilities of SWM spacers reported for the first time.
- Spacer/fabric thickness variation with imposed pressure accurately measured.
- Permeate-side permeabilities are essential for SWM design/performance simulation.

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ABSTRACT

Reliable estimates of the effective lateral permeability (k) of permeate-side spacers of spiral wound membrane (SWM) elements are required in order to design them and simulate module and plant performance. Such permeability data are not available at present. A straightforward approach is recommended for determining k of spacers under modest pressure, which involves pressure drop measurements in a spacer-filled channel coupled with separate accurate data on the effect of normal pressure on spacer thickness. Application of this approach to typical spacers from commercial SWM modules shows that k is at the level of 2 to 3.5×10^{-10} m^2, for measured thickness 0.20 to 0.25 mm. The tested spacers exhibit modest compaction under pressure, with a tendency to approach asymptotically a minimum thickness at a pressure smaller than that prevailing in tightly wound membrane envelopes of commercial modules. Recommendations are also outlined regarding R & D directions on the selection of appropriate permeate spacers in the context of overall optimization of SWM module design and desalination process performance.

1. Introduction

Spacers of both the retentate and permeate side of SWM modules separate membrane sheets and create the necessary flow passages [1,2]. The detailed geometrical characteristics of both types of spacers (and the flow channels they create) determine, to a large extent, the overall performance of SWM elements [3–8]. To ensure SWM element integrity and overall rigidity, in the presence of large axial forces (thrust) due to the high pressure feed flow, membrane envelopes with the spacers are wrapped around the inner (permeate) tube very tightly during manufacturing [1,8]. Consequently, both membranes and spacers are subject to quite large stresses in a direction normal to the SWM element axis [8]. Furthermore, during high pressure RO desalination, additional normal stresses are experienced by the permeate spacer due to the high pressure prevailing at the retentate side [8].

These SWM element overall structural characteristics and operating conditions essentially impose the design criteria for both types of spacers. In the case of retentate side spacers, emphasis is placed on the fluid mechanical aspects of spacer performance [3–9]; indeed, the relatively high cross-flow velocities, required to mitigate concentration polarization and fouling phenomena, dictate the use of a rather sparse net-type structure of spacers to minimize pressure drop [4,5,7]. However, permeate side spacers should mainly provide satisfactory (even at a small length scale) backing to the membrane, whereas their porosity should be sufficiently large to facilitate the Darcy type flow of the permeate towards the collecting tube; thus, permeate spacers of SWM commercial elements are in the form of a relatively dense fabric made of woven thin plastic fibers [1,8].

Over the past 10–15 years retentate-side spacers have received a great deal of attention (e.g. [3–7,9–13] due to their above-mentioned importance in shaping the flow field at the active membrane surface, thus, significantly influencing the effectiveness of separation. Considerable progress has also been made in understanding the effect of retentate spacer geometrical details on the flow field and transport

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phenomena within the respective narrow channels (e.g. [4–6]). On the contrary, permeate-side spacers and their permeability characteristics have been practically ignored by researchers, who might have been influenced by the commonly made (incorrectly for real size SWM elements [14,15]) assumption of negligible pressure drop in the permeate channels. Yet, failures in industry to predict the productivity of new large SWM elements (during their development [16,17]) are directly related to the lack of understanding of permeate side pressure drop effects in connection with the membrane width. Moreover, from an industrial point of view, in a recent illuminating account of R&D needs for improved SWM design, the significance of permeate spacers is stressed [8].

Regarding a quantitative characterization of RO-membrane permeate spacers, very little and of questionable value is available in the open literature, to the best of the authors knowledge. In an often quoted paper on membrane modules [18], some pressure drop data from narrow channels with permeate spacers are presented and a correlation is suggested. The usefulness of these data is limited since the permeate flow distribution in the respective channels (of commercial elements) is highly variable, necessitating a reliable computational tool for predicting design and performance of the entire SWM module. Such tools in the form of integrated algorithms (e.g. [15]) require values of an *intrinsic* property of the spacer (i.e. its permeability) to enable computations of all relevant process parameters throughout a membrane sheet and further throughout the SWM element. As this type of information is unavailable, the present publication outlines a method for accurate determination of the *effective lateral permeability of a permeate spacer constrained by two parallel plates under pressure*. This is the kind of permeability needed as an essential input to a comprehensive computational tool to simulate, in a reliable manner, the performance of the entire SWM module for desalination and water purification applications.

2. Method to determine spacer permeability

2.1. Principle

Darcy's law describes the small-velocity flow within the permeate narrow channels with spacers. Considering one-dimensional flow in the x-direction, through the spacer-filled channel of cross-sectional area $A = (w \cdot h)$, one obtains:

$$\frac{Q}{w \cdot h} = \frac{k}{\mu} \frac{\Delta P}{\Delta x} \tag{1}$$

where k is the effective permeability (m^2), μ the dynamic viscosity (Pa·s), Q the flow rate (m^3/s) and $(\Delta P/\Delta x)$ the pressure drop per unit length (Pa/m). The effective spacer thickness (or channel gap) h which is at the level of 0.2 to 0.3 mm for RO membrane elements, should be accurately measured for a channel of constant width w. Therefore, the effective lateral spacer permeability k can be determined experimentally from the slope $\left[\frac{k \cdot h \cdot w}{\mu \cdot \Delta x}\right]$ of the linear expression correlating pressure drop ΔP versus Q data; i.e.

$$Q = \left[\frac{k \cdot h \cdot w}{\mu \cdot \Delta x}\right] \Delta P \tag{2}$$

It should be stressed that for the purpose of this investigation, it is also necessary to study the possible effect of pressure, exerted by the two bounding parallel plates, on the deformation (i.e. the reduction of thickness h) of the sandwiched spacer. In this manner, the conditions prevailing in the permeate channels of real SWM modules can be satisfactorily simulated.

2.2. Experimental techniques

The main experimental set-up for measuring pressure drop versus flow rate though a spacer-filled channel is presented in detail elsewhere [4,5]. The test-section is comprised of two parallel Plexiglas plates (each 2.5 cm thick), forming a narrow channel with gap h adjusted by a special flange, depending of the thickness of the particular spacer to be tested. The free flow length and width in the channel are 40 cm and 14.5 cm, respectively. To investigate the effect of spacer compression on pressure drop, four special clamps were fixed along the main symmetry axis (in the x-direction) of the test section at equidistant locations. Uniform pressure was applied on the two plates (transferred to the spacer) by tightening all the clamps uniformly through a torque wrench. Several sets of $\Delta P/\Delta x$ versus Q measurements were taken, for various fixed applied pressures, by progressively tightening (step-wise) the clamps, thus increasing the compressive stresses on the spacer. Accurate independent measurements of thickness h are subsequently outlined. The permeability k is finally computed through the following expression.

$$k = \frac{1}{h}\left[\frac{\mu Q}{w(\Delta P/\Delta x)}\right] \tag{3}$$

The channel gap (i.e. the effective spacer thickness h) in the above flow tests could not be measured with the required accuracy. Therefore, in order to investigate the effect of normal pressure on spacer thickness variation, precision measurements were made in an advanced rheometer, namely AR-G2 (TA Instruments), using parallel plate geometry. This system, described elsewhere (e.g. [19]), is a versatile and precision instrument, mainly for rheological measurements; however, in its parallel plate operating mode, it is also most appropriate for precision thickness measurements of thin films of deformable materials. This instrument allowed very accurate simultaneous measurements of both spacer/fabric thickness h and normal pressure applied to the spacer, by operating in the 'squeeze/pull off' test mode. Specifically, a specimen was fixed perfectly flat on the system *Peltier plate* by means of a special stainless steel hollow cylinder [19]. A 20 mm diameter metal disc (perfectly parallel to the Peltier plate) could move vertically at a very small, controlled rate of descend (of order 0.5 μm s^{-1}). At each vertical disc location, the distance h from the reference base plate (i.e. the apparent fabric thickness) as well as the applied pressure were recorded.

Two types of measurements were made, i.e. one with a dry spacer specimen and another with the spacer fabric wetted through immersion in water; in the latter case the spacer voids were filled with water. In this manner, accurate profiles of thickness h variation with applied pressure could be obtained. By combining the pressure drop measurements, with appropriate values of thickness h, the effective spacer permeability can be accurately determined (through Eq. (3)) under various conditions as shown in the following.

3. Results and discussion

Three kinds of permeate spacers (to be referred to as "A", "B" and "C"), from three commercial RO membrane elements, of two well-known manufacturers, were employed to demonstrate the aforementioned techniques and to determine their effective permeability. All three samples have the texture of a relatively thin, yet somewhat stiff, fabric. Figs. 1 and 2 include Scanning Electron Microscope (SEM) images of spacers A and B, respectively, which show that both are made of woven bundles of very thin fibers. The two sides of the spacer/fabric are quite different at the microscopic level. It will be noted that in a SWM element the RO membrane support layers (comprising a membrane envelope) are in contact with such dissimilar and uneven sides/surfaces of the spacer. Therefore, one may wonder whether the RO membrane (usually of thickness ~150 μm) can suffer significant deformation, during the high pressure desalination operation, due to this uneven backing; such deformation might modify the permeate channel geometry with negative impact on pressure drop. RO membrane deformation due to much thicker (net-type, rather