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The effect of spiral wound membrane element design characteristics on its performance in steady state desalination — A parametric study

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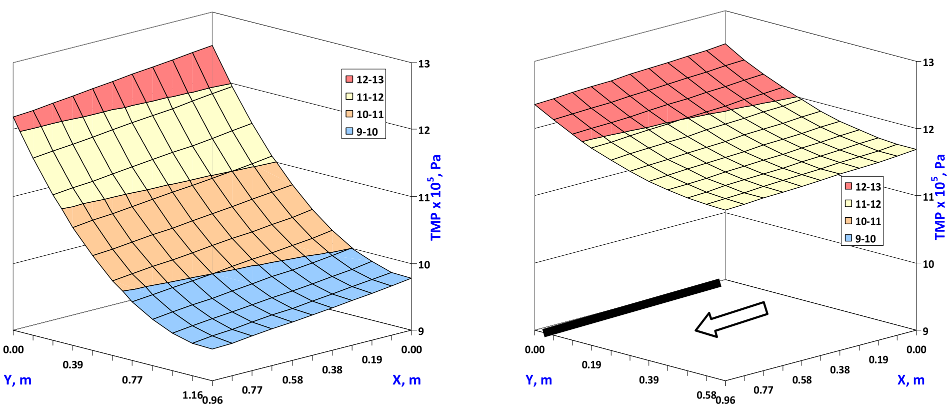
HIGHLIGHTS

- Novel advanced simulator of SWM element steady-state desalination performance
- Systematic study of SWM performance sensitivity to geometric design parameters
- Permeate- and retentate-spacers mainly affect SWM productivity and pressure drop.
- The strong effect of membrane envelope width on SWM performance is confirmed.
- Results helpful in guiding SWM module optimization and in setting R&D priorities

GRAPHICAL ABSTRACT



Spatial trans-membrane pressure distribution throughout large (left)and small (right) membrane envelopes in brackish water desalination.

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ABSTRACT

The spiral-wound membrane (SWM) element design variables include retentate- and permeate-spacer characteristics and number of membrane envelopes (or sheet width) for constant total area, in addition to membrane surface properties. The effect of these parameters (varying within realistic ranges) on the operating variables, comprising two-dimensional distribution of permeate flux, trans-membrane pressure (TMP), retentate- and permeate-side pressures and velocities, is systematically assessed. Advanced software is employed, capable of simulating SWM desalination performance with no recourse to empirical parameters. The parametric study involves typical cases of desalinating brackish and sea-water with 2000 mg/L and 40,000 mg/L TDS, respectively, in pressure vessels with seven 8-inch SWM-elements. The results show that low-pressure desalination modules are most sensitive to variations of geometric parameters. The effect of permeate-side fabric is significant, directly affecting TMP and module productivity. In both low- and high-pressure desalination, the effect of retentate-side spacer manifests itself mainly in the pressure drop across the element. The results confirm that the membrane width is very important, with short sheets exhibiting the best overall performance. Noteworthy is the insensitivity of high-pressure SWM-module productivity to significantly different design parameter-values, including envelope width. These results are helpful in guiding SWM element optimization and in setting priorities for related R&D work.

1. Introduction

The central role of membrane technology, in solving the global problem of water scarcity, and its tremendous growth potential are broadly recognized. Therefore, ever-increasing R&D efforts are made to develop

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this technology to the maximum extent possible, mainly aiming at reduction of product-water unit cost and mitigation of environmental impact [1,2]. Achieving these targets, hinges on the optimum design and performance of the SWM modules, which are well established as the dominant component of modern Reverse Osmosis (RO) and Nanofiltration (NF) plants. Consequently, some aspects of design and operation of this component have received a great deal of researchers' attention, which has intensified after approx. 1998 when the SWM became the essentially unchallenged choice in all major membrane desalination plants.

The development of SWM module to the presently used form, including its invention almost 50 years ago [3], has been the outcome of *ingenious engineering*; concurrently, the much improved membrane surface characteristics, since the early days of cellulose acetate [3–5], have been made possible through *scientific progress* in the field of materials [1]. Regarding the module arrangement in plants and the related equipment developments, significant improvements have been made (e.g. [6,7]), mostly to accommodate the SWM elements in series within the pressure vessels (without leaks), while maintaining their integrity (i.e., by anti-telescoping devices, special O-ring arrangement, etc.). However, it is interesting that the morphology of SWM module itself has been essentially unchanged over the past four decades. Even the very recent development of the large 16- and 18-inch modules (itself another engineering feat) is based on the same membrane envelope arrangement and general morphology. Similarly, planning [8] of even larger (24-inch) modules apparently follows the same pattern.

The compact design of SWM modules allows packing a large membrane surface area per unit volume, but it is also characterized by very narrow spacer-filled channels (of gap less than 1 mm), which tend to aggravate operating problems (i.e. friction losses, membrane fouling and scaling); moreover, this design poses serious challenges to R&D efforts aiming to study in detail and understand module performance. In particular, despite some progress made in recent years (e.g. [9]) detailed/local non-invasive measurements inside real modules are almost impossible to make, thereby depriving researchers and technology developers of essential information. In fact, only data on *average* SWM module operating parameters can be obtained as well as information from post mortem element autopsies to determine fouling patterns, which have obvious limitations. These difficulties have significant consequences in approaches taken to design and to investigate large size SWM modules. On the former, papers originating from industry (e.g. [10,11]) suggest that, in the development of large size elements, time-consuming "trial-and-error" approaches were followed, as apparently no reliable predictive design tools were available. Indeed, Yun et al. [10] reported that the specific flux [gal/ft^2/day/psi] of a new (under development) 16-inch element, using long-width leaves, was found to be clearly inferior to that of shorter leaves (and even to that of standard 8-inch SWM elements); the longer width 16-inch element under development (1st generation) also exhibited significantly greater fouling. Lomax [11], in an interesting account of SWM industrial developments, reported similar findings in early efforts to develop 12-inch SWM elements. In a recent paper, Johnson and Busch [7] provide a comprehensive industrial perspective on SWM module design parameters, outlining uncertainties and areas for improvement.

The literature on modeling the operation of SWM modules is rather extensive. A recent brief review of relevant models, their structure and main features is provided elsewhere [12]; therefore, only some comments on relevant literature are made here. Schwinge et al. [13] provide a fair account of SWM design issues and modeling studies (up to ~2004), and a more recent review is also available [14]. It is interesting that in SWM-scale models, usually the permeate-side is not taken into account (assumed to be in constant pressure), which renders the retentate-side model one-dimensional; this simplification is made even in very recently reported models [14]. A recent model [15], used to simulate long term operation of a desalination plant, is based on a dynamic one-dimensional fouling model where concentration polarization is accounted for [16] neglecting permeate pressure drop. In older two-dimensional modeling studies [17,18], where specific solution approaches are followed, global results are presented for the permeate side variables, but not for their detailed distribution throughout the membrane sheets. However, the two-dimensional model by van der Meer et al. [19] is interesting as it provides insights into the influence of main SWM parameters (including the number of leaves) on the performance of an NF element. Even though this model includes simplifying assumptions, untested empirical correlations and some unrealistic parameter values (e.g. membrane sheet width 2.8 m) the qualitative results appear to be generally correct. Avlonitis et al. [20] developed software, aiming at predicting brine and permeate characteristics for the SWM modules in pressure vessels, based on analytical solution of two-dimensional flow in membrane elements, with significant simplifications. Good agreement was reported between predictions and (one-dimensional) data obtained from an operating RO seawater desalination plant, but the model performance and sensitivity were not examined over a sufficiently broad range of parameter values. Very recently, a comprehensive two-dimensional model was developed [12], for flat-sheet membrane modules. The distribution of all process parameters (at both flow compartments, throughout the membrane envelop) can be predicted, as a function of the design variables; thus an advanced simulator based on this model is most appropriate for SWM parametric studies (of the type presented here) and for module optimization.

The scope of this paper is to systematically investigate the sensitivity of SWM element performance (reflected in the 2-D distribution throughout the membrane sheets, along a pressure vessel, of all operating parameters) to variations in the main SWM geometrical design parameters; i.e. *the membrane envelope number and/or width, and the retentate- and permeate-side spacer geometrical characteristics, including the respective channel gaps*. This sensitivity study has been performed in a range of parameters typical of those prevailing in brackish- and sea-water membrane desalination applications. This study aims to identify, in a theoretically sound manner, trends in parameter variation (some intuitively expected or established empirically by trial and error) toward SWM performance optimization, that would be helpful to both technology developers and researchers. The latter are expected to develop a better appreciation of the desirable range on SWM element design and operating parameters, on which they should focus in R&D studies.

2. SWM element design and operating parameters — parametric study data

2.1. SWM design and operating parameters, and related problems

The morphology of SWM elements is well-known (e.g. [4,5]). The currently used standard 8-inch elements are approximately 1 m (40 inch) long. However, there is no standard width of the membrane sheets; i.e. in several well-known commercial modules this width is in excess of 1 m and in some other less than 1 m. A membrane envelope is made of two sheets, glued at the three edges, with a fabric filling the permeate channel. The open permeate side of this envelope is fixed/glued on a perforated inner tube where the permeate is collected. Several envelopes, separated by relatively thin net-type spacers, are tightly wrapped around the permeate collection tube. The spacer-filled narrow channels, where the high pressure feed and retentate flow, are a key feature of the SWM modules, playing a very important role in the filtration process, as will be subsequently described. However, the permeate channel flow and fabric/spacer, largely neglected so far [7,21], merit particular attention as they appear to play a significant role in SWM performance [13,19,20].

Major membrane module *design characteristics*, in need of optimization, include

- the physico-chemical characteristics of membrane active surface,
- the geometrical characteristics of retentate- and permeate-side spacers and