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Analysis of the influence of module construction upon forward osmosis performance

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ABSTRACT

The potential of a commercial forward osmosis (FO) module to recover water from NEWater brine, an RO retentate, was assessed by taking an innovative approach to obtaining the mass transfer coefficients. The performance comparison of the spiral wound (S-W) FO module with that of the flat sheet laboratory unit suggests that the winding involved in S-W construction can adversely affect performance; the values for the S-W mass transfer coefficients were half of those expected. This first-of-its-kind performance comparison utilised coupons of the membrane and spacers taken from the module. The module was used both in the conventional manner for FO and in the reverse manner with the active layer facing the draw solution. Estimates of membrane parameters and mass transfer coefficients experiments for the two orientations were obtained using pure water, 10 mM and 25 mM NaCl solution on the feed side and 1 M NaCl as draw solution. The fouling potential of NEWater brine *per se* was found to be low. These are the first results with a S-W module that suggest potential for this niche application; nevertheless the level of the water flux through the S-W module clearly indicates that industrial applications of S-W FO will be constrained to special cases.

1. Introduction

It is appropriate in an issue in honour of Professor Raphael Semiat that we should be analysing the influence of module construction upon overall performance. In this study the performance of a commercial spiral wound Forward Osmosis (S-W FO) module is compared with that of a bench-scale flat sheet unit incorporating membrane and spacers cut from the S-W FO module. A significant difference was found experimentally and explained through an analysis of mass transfer. We have noted with great interest a recent paper by Semiat and co-workers on an analysis of FO mass transfer resistances via CFD analysis and film theory [1]. In that paper the use of 2D finite element CFD model and the common film model (FM) were compared and it was concluded that the FM model over-estimates the significance of the permeation resistance of the FO membrane support layer. As the present study is a comparative one between module types (S-W FO *vs* flat sheet laboratory unit) we have used the traditional approach for the analysis, especially as a CFD analysis has not been undertaken. However it is noted that Sagiv et al.'s [1] conclusions are in accord with our recent FM based study [2] and other CFD [3,4] ones in questioning the oft reported dominance of the contribution of the internal concentration polarisation (ICP) over that of external concentration polarisation (ECP). Contrary to popular wisdom some analyses [*e.g.* 1] suggests that improvements in FO water permeability are in part more likely to emerge from improved channel hydrodynamics (to decrease external concentration polarisation) rather than from more permeable and thinner membrane support layers. Here we compare the mass transfer characteristics of a S-W FO module with that of a standard flat sheet laboratory unit in order to assess the influence of construction upon performance.

At this stage it is customary in papers on FO to say that osmotically-driven membrane processes represented by (FO) and Pressure Retarded Osmosis (PRO), are emerging membrane technologies that show great promise to address the global challenges in water and energy supply. The paper may even continue, as in [5], to say with regard to PRO that "it did not achieve rapid advancement until the operation of the first prototype PRO osmotic power plant in Norway in 2008" and then completely fail to say that the Statkraft prototype (which was formally opened on 24 November 2009) was closed in 2014. Furthermore the facility had produced power at just 2–4 kW. It was reported that the Norwegian power company Statkraft had shelved its efforts because the technology could not be sufficiently developed within the current

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market outlook to become competitive "within the foreseeable future" [6].

The outlook for osmotically driven processes is not as rosy as generally portrayed. Firstly it is widely recognised that the water flux in an osmotically driven process is severely limited by "concentration polarisation" [2,7] which arises either by dilution of the high-osmotic-pressure draw solution (FO mode) or undesirable concentration of the feed solution inside the FO support structure (PRO mode). Secondly there are challenges in designing compact modules [2,8] and as noted above ECP can also cause a very significant constraint. Due to this, two of the current authors have expressed strong doubts as to whether forward osmosis will ever successfully compete with reverse osmosis for desalination of seawater because of inherent mass transfer limitations [2]. From a solid theoretical analysis it was concluded that the future of forward osmosis probably lies with niche applications of very high salinity brines [2]. It is now generally accepted that FO will not compete with reverse osmosis for desalination of seawater and that if FO has a widespread future beyond niche applications it will involve the brine from traditional RO plants acting as the draw solution. The potential of recovering water from NEWater brine, currently a reject stream, will be discussed at the end of the paper in Section 4.

As noted by others [9] numerous academic groups around the world have made new membranes for forward osmosis but at full-scale production the dominant platform has been a cellulose acetate membrane from Hydration Technology Innovations (HTI). Whilst [9] reported on a newly launched forward osmosis membrane from HTI, namely their thin film composite (TFC) membrane, our study was based on their traditional cellulose acetate membrane.

2. Materials and methods

2.1. Chemicals and membranes

Unless otherwise specified, all the chemicals used in this study are ACS grade and all the solutions were prepared using ultrapure water with a resistivity of 18.2 MΩ cm produced by a Mill-Q system (Millipore Integral 10 Water Purification System). In all experiments 1 M NaCl was used as draw solution. For the work at pilot scale, tap water was used in the preparation of the draw solution. The NEWater brine was delivered in 25 L carboys.

The osmotic membrane used in this study was a commercial FO membrane, FO Spiral Elements SepraMem 4040 FO Standard Spacer by Hydration Technologies, Inc. (HTI, Albany, OR). It is shown in Fig. 1. This membrane has an asymmetric structure and is prepared by coating cellulose triacetate (CTA) into a polyester mesh [10]. It has been reported that the membrane itself has a thickness of less than 50 μm [11].

The dimensions of the module element are given in Fig. 2. This diagram has been drawn for PRO mode *i.e.* AL-DS orientation. The spacer on the draw side was 0.87 mm thick. The one on the feed side was 0.64 mm thick and was in two pieces reflecting the fact that there is a central seal over 70 cm of the element – see Fig. 1 (right) and Fig. 2.

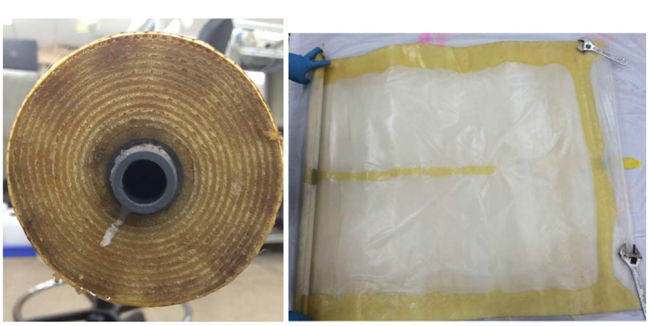

Fig. 1. Cross-sectional view of the spiral wound CTA membrane taken out of its module casing (left) and unwound (right).

The mesh sizes are also different as shown in Fig. 3.

2.2. Pilot-scale set up and experiment

The feed solution (FS) and the draw solution (DS) were re-circulated, without concentration correction. Draw solution from the draw tank was pumped into the membrane element through a booster pump (BP), whilst a low pressure pump (LP) was used for the feed. Both pumps could have been low pressure pumps for the current work because in FO $\Delta p \sim 0$ but the rig had been designed to enable PRO operation as well as FO operation. The pumps were operated using computer control. A schematic of the layout is given in Fig. 4. More details can be found in [19].

DS and FS tanks initially contained 100 L of 1 M NaCl solution and 100 L of 25 mM NaCl solution respectively at the start of the baseline tests. Subsequently the tests involved 100 L of 1 M NaCl solution and 100 L of NEWater brine. The NEWater brine solution is a retentate of sewage waste water that has been treated through dual membrane processes, firstly microfiltration and then reverse osmosis. The waste water that is not recycled for re-use is the retentate brine from the RO stage; the permeate from the RO stage is then UV treated. NEWater Brine was collected from a NEWater factory in Singapore. The 25 mM NaCl solution was used for the baseline tests because it has similar conductivity to NEWater brine. Tap water was used for dilution of the NaCl solutions. All tests started with the DS and FS tanks containing 100 L at appropriate concentrations.

During the runs, which were of 4 hour duration, the feed solution gradually became concentrated as a result of permeation of water from feed side to the draw side. This also resulted in dilution of the draw solution. By noting the conductivity values of solutions on both sides at the start and end of each run, the change in osmotic pressure difference could be estimated. Before moving to the next run, both solutions were adjusted to approximate levels. For the feed solution, tap water was added to the feed solution up to the level of the previous run and for the draw solution, 5 M NaCl was added as required until the conductivity of the draw solution matched that of 1 M NaCl solution. When analysing the results the mean concentrations during the 4 hour runs were used to calculate the overall driving force as the change in concentrations were modest being around 15%.

The six runs with NEWater brine reported here were alternated between the AL-DS orientation and the AL-FS orientation. The orientation was reversed by simply interchanging the feed and draw tubings connecting the FS and DS tanks to the module. Before switching, the draw side was flushed thoroughly with tap water to remove any remaining salt.

2.3. Bench-scale set up and experiments

The bench-scale FO setup was essentially the same as that used elsewhere [12] except for the membrane cell which has identical channels on each side; the dimensions are a length 85 mm and a cross-sectional flow area of 39 mm by 2.3 mm. These experiments used membrane coupons cut from the spiral wound modules and spacer material was also cut and placed in the channels but skims to ensure a tight fit were not used. (As noted later this may have been fortuitous.) The computer controlled system with conductivity measurements and automatic dosing ensured that feed and draw concentrations remained constant. Two variable-speed peristaltic pumps were used to recirculate the respective feed and draw solutions at a flowrate of 0.4 L/min which gave a crossflow velocity of 0.074 m/s. The flow rates were not chosen to correspond to those used in the pilot scale set-up thus a classical mass transfer correlation was used to link the results from the two sets of experiments. The volumetric flux of water was determined at regular time intervals by measuring the mass changes of the feed tank; it was on a digital mass balance connected to a computer data logging system.

A limited number of reverse osmosis baseline experiments were