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Practical considerations for operability of an 8″ spiral wound forward osmosis module: Hydrodynamics, fouling behaviour and cleaning strategy

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HIGHLIGHTS

- An 8″ commercial spiral wound CTA and TFC FO modules were investigated.
- TFC module showed much higher permeability and selectivity in FO and PAO modes.
- Draw flow rate in the CTA modules must be operated at least 5 times lower than feed flow rate.
- In practice, feed pressure could be considered as an indicator of fouling occurrence.
- The combination of osmotic backwash and physical cleaning is effective for cleaning CTA and TFC modules.

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ABSTRACT

A better understanding of large spiral wound forward osmosis (SW FO) module operation is needed to provide practical insight for a full-scale FO practical implementation desalination plant. Therefore, this study investigated two different 8″ SW FO modules (i.e. cellulose tri acetate, CTA and thin film composite, TFC) in terms of hydrodynamics, operating pressure, water and solute fluxes, fouling behaviour and cleaning strategy. For both modules, a significantly lower flow rate was required in the draw channel than in the feed channel due to important pressure-drop in the draw channel and was a particularly critical operating challenge in the CTA module when permeate spacers are used. Under FO and pressure assisted osmosis (PAO, up to 2.5 bar) operations, the TFC module featured higher water flux and lower reverse salt flux than the CTA module. For both modules, fouling tests demonstrated that feed inlet pressure was more sensitive to foulant deposition than the flux, thus confirming that FO fouling deposition occurs in the feed channel rather than on the membrane surface. Osmotic backwash combined with physical cleaning used in this study confirmed to be effective and adapted to large-scale FO module operation.

1. Introduction

The most commonly used desalination technologies are generally pressure-based membrane processes such as reverse osmosis (RO) and nanofiltration (NF). However, the wider development of these processes is often limited due to high membrane fouling and scaling propensity and high energy consumption, resulting in operation and maintenance costs [1–3]. As a potentially more sustainable alternative, the use of forward osmosis (FO) has been recently put forward and extensively investigated. In FO, the driving force is an osmotic pressure gradient, allowing water to naturally flow from a low chemical potential feed solution (FS) to a concentrated high chemical potential draw solution (DS) through a semipermeable membrane [4,5]. Although direct cost comparison of FO with conventional NF and RO systems remains a challenging task, several studies have demonstrated that desalination by FO could lead to lower energy consumption, reduced fouling propensity and higher cleaning efficiency [5–7].

Recent interest in FO applications has been particularly driven by the performance improvement offered by the latest generation of FO membranes. The improvements include higher water permeability, greater selectivity and rejection, smoother active layer surface allowing lower

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fouling propensity, and quite importantly, a specifically adapted porous support layer offering low internal concentration polarization (ICP) yet still appropriate mechanical support for practical operation [4,5]. The first commercially available and specifically tailored FO membranes, based on cellulose triacetate (CTA), were developed by Hydration Technology Innovations (HTI, Albany, OR), and have been examined in various applications by numerous research groups [8–13]. More recently, thin film composite (TFC) FO membranes were designed with a polyamide selective layer, and these feature higher water flux and better solute rejection compared to CTA membranes [14–17]. In addition, TFC membranes were found to be more pH stable and were more resistant to hydrolysis and biological degradation [17–19]. In contrast, previous studies have reported that TFC membranes showed higher fouling tendency than CTA membranes due to the increased surface roughness [17,18,20,21]. As such opportunities to increase flux with commercially available membrane exists, but long-term fouling studies are required. An optimised FO module design is expected to feature high membrane packing density, lower concentration polarization (i.e., high mass transfer coefficient) and high water permeation [22]. Performance of several commercial FO membranes (i.e., Porifera and Toyobo) has been widely reported in the literature on small membrane samples but information regarding module design is still limited since most commercial FO membrane modules are still under development. Only the performance of SW FO modules developed by HTI has been reported for a variety of feed and draw spacers (fine, medium and corrugated spacer) [12] while detailed information on other suppliers module configurations are not available. This clearly indicates that CTA and TFC membrane modules were the most mature and developed membranes during the time of this FO study. In this regard, most studies so far were conducted using small flat sheet membrane coupons which are not always representative of behaviour in full-scale modules. Therefore, a better understanding of FO behaviour in larger modules is needed to provide more practical insight for full-scale FO operation.

A large-scale spiral wound (SW) FO module typically requires four ports: two inlets and two outlets for both the FS and DS. In SW FO modules, the FS circulates in the feed channel between the rolled layers, and the DS flows through the central tube into the inner side of the membrane envelop [23]. Therefore, flow patterns and flow resistance in the feed and draw channels can be different and affected by specific module design. In particular, a more detailed study linking operating conditions (flow rates, inlet pressures) to resulting performances (water flux, reverse salt flux, fouling and cleaning efficiency) of SW FO modules will provide important insights in the operability of current SW FO modules on full-scale.

Very limited pilot-scale FO studies using SW FO modules currently exist in literature [23–25]. However, these pilot studies are of crucial importance for further FO development since the operation of SW modules in industrial plants is affected by several factors such as the number of membrane leaves, feed and draw channel height, spacers that affect mass transfer and pressure loss, but also fouling potential [26]. To the best of the author's knowledge, so far only two studies have been reported in literature using 4040 SW (4″ in diameter and 40″ in length) [24] and 8040 SW (8040, 8″ inch in diameter and 40″ in length) [23] HTI CTA FO modules. Those studies mainly focused on the optimisation of a large-scale SW FO module [24] and of a newly proposed fertiliser drawn forward osmosis process for a specific application [23,27]. However, the susceptibility of SW FO modules to membrane fouling during the long-term FO operation has not been considered in those studies, which could consequently exacerbate the performance of in full-scale FO stand-alone or hybrid process. Although membrane fouling on the feed side in FO happens less and is easily removed by simple physical cleaning [3,28,29], the effect of osmotic backwash seems to be unclear. Some studies have reported that the osmotic backwash could lead to an adverse effect on the driving force due to the accumulation of the reversed solutes within the fouling layer [29–31]. Nevertheless, the specific combination of osmotic backwash with subsequent physical cleaning could be more effective to restore a significant portion of water productivity after fouling occurred [32]. Thus, there is a critical need to control operating conditions and assess performances of SW FO modules more systematically including fouling behaviour and cleaning strategies for sustainable FO operation.

As an alternative to FO, a new FO-derived concept called pressure assisted osmosis (PAO) has recently been developed. PAO is aimed at increased water production compared to FO for more favourable economics for further commercialization [32–36]. In PAO, hydraulic pressure is applied on the feed side of the membrane to enhance the water flux through the synergistic effects of hydraulic pressure and osmotic pressure [32–36]. Overall, it has been demonstrated that by increasing the applied pressure, the water flux was significantly improved despite higher ICP. Even more than for FO, the role of a spacer in the PAO process is important to prevent the deformation and damage of the membrane caused by the applied hydraulic pressure on the feed side of the membrane [34,36,37]. This reinforces the need to evaluate the impact of hydraulic pressure on the module-scale FO and PAO operations.

Accordingly, there is a clear need for a detailed assessment of the impact of hydrodynamic conditions on pressure behaviour of an SW FO module (i.e. build-up in draw stream and drop along feed line). This study therefore systematically studied the performances of two commercial SW FO modules (CTA from HTI and TFC from Toray Industries Inc.). An assessment of the water flux and reverse salt flux behaviours as a function of operating conditions in both FO and PAO operation was conducted to evaluate the performance of both modules compared to lab-scale experiments. Fouling studies were performed with a mixture of model organic foulants was then used to evaluate the fouling behaviour and cleaning strategies for the modules operated in a seawater dilution application. To our best knowledge, this is the first study addressing the practical operations of commercially available 8″ SW FO modules and providing a comparative assessment of long-term fouling behaviour in large-scale FO process. Therefore, the results reported in this study can be useful for further investigation of the fouling control by chemical cleaning and/or pre-treatment in full-scale FO operation.

2. Material and methods

2.1. Spiral wound FO membrane module

Two different 8″ SW FO modules were used (Table 1): one CTA module manufactured by HTI and one TFC polyamide module manufactured by Toray Industries, Korea. In both modules, the rejection layer of the membrane faces the FS and the porous support layer of the membrane faces to the DS. Feed and permeate spacers were present to keep the membrane leaves apart [23,24].

As presented in Table 1, the CTA module had a corrugated feed spacer made of 2.5 mm polystyrene chevron and an effective membrane area of 9 m^2 with six membrane leaves. The TFC module had a feed spacer made of a 1.19 mm diamond type polypropylene mesh and an effective membrane area of 15 m^2 with ten membrane leaves. In addition, both modules had different permeate spacers: the CTA module had three tricot spacers, while the TFC module featured a draw channel containing one diamond type spacer wedged in between two tricot type spacers. If a net spacer is used inside of the envelope in the SW FO module and the DS side is pressurized, the feed flow channel may be blocked by membrane deformation. Accordingly, a tricot fabric spacer is used inside the envelope like a permeate carrier of an SW RO module and prevents the membrane deformation and this structure has been already utilised for pressure-retarded osmosis application [38]. Water permeability (A) for both FO modules was measured in RO mode in a pilot-scale FO unit (tap water - conductivity 240 ± 20 μm/cm - in the feed and draw sides). The tests were conducted at increasing feed pressures (in intervals of 0.5 bar up to 2.5 bar). A_{CTA} and A_{TFC} were found to be 1.6 ± 0.2 and 8.9 ± 0.14 $Lm^{-2}\ h^{-1}\ bar^{-1}$, respectively. Additional information on the properties of the CTA and TFC FO membranes such