TECHNICAL NOTE

Permeate recovery and flux maximization in semibatch reverse osmosis

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Most reverse osmosis (RO) and nanofiltration (NF) processes operate as once through or plug flow (PF) systems in which permeate recovery, flux and cross-flow are coupled. Such processes are well suited for applications where permeate recovery percentages are limited and where well pretreated source waters of uniform composition are available. Some membrane filtration applications, such as ultrafiltration, operate as batch systems. Batch operations allow independent manipulation of permeate recovery, flux and cross-flow, and are therefore well suited for high recovery and/or problematic source waters. However, the application of batch operation to RO and NF has been limited because of the increase in energy requirements and reduction in permeate quality that can result. In addition, batch systems can require higher capacity components and more membrane elements and housings than comparable continuous or plug flow systems to compensate for downtime between batches. New semibatch or continuous batch processes for RO or NF applications are emerging. These processes provide high adjustable recovery rates, independently adjustable cross-flow and resistance to and even reversal of fouling and scaling. They can consume less energy and require fewer membrane elements than PF systems. High recovery operation reduces both concentrate production and source water pumping and pretreatment requirements. High cross-flow, reduced lead element flux, more even flux distribution and salinity cycling can reduce the effects of fouling and scaling and the associated chemical and cleaning requirements. These features are particularly beneficial for inland desalination, wastewater concentration and water reuse applications. This paper considers process designs and projected membrane performance of semibatch RO systems for brackish and low salinity source waters. The potential advantages of new process design features that can be employed in batch RO but are not practical for conventional RO, such as short membrane arrays and high recovery single stage designs, are evaluated. Particular focus is given to the operating conditions and performance of individual membrane elements in multi-element membrane arrays. Comparisons are made to the performance of conventional PF RO designs. The analysis will help engineers of RO and NF systems to understand the new capabilities, optimization considerations and potential new applications for this emerging process technology.

Keywords: Reverse osmosis, Nanofiltration, Semibatch, Flux, Recovery

Introduction

Industry is responsible for almost 60% of the fresh water withdrawals in the USA, and industrial demand is similarly high in developed countries around the world (UNESCO, 2003). Treatment of this water to meet industrial source or discharge requirements necessitates use of excess raw water and produces an effluent stream that must be disposed of or further treated. This puts tremendous pressure on water resources, which will only increase with growth. Water supply and effluent disposal costs have already become a burden and even a limiting factor for many industrial operations. There is no doubt that with this trend, more efficient use of water with high recovery water treatment methods and water recycling and reuse will become standard.

Most filtration methods, including simple filtration, multimedia filtration, micro- and ultrafiltration, ion

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exchange and activated carbon treatment, operate as batch systems. The product water flow coming from the filter equals the feed flow going to it and filtrates are retained in the system. Periodically, the filtrates are dumped and/or rinsed. The product water recovery rate, flux and cross-flow can be independently manipulated in these systems, making them well suited for high recovery and/or problematic source waters.

Reverse osmosis (RO) and nanofiltration (NF) are typically not implemented as batch processes. Rather, they operate as once through or plug flow (PF) systems in which permeate recovery, flux and cross-flow are coupled. Recovery rates of less than 75% of the water fed to the membranes are typical, with a corresponding reject rate of 25%.

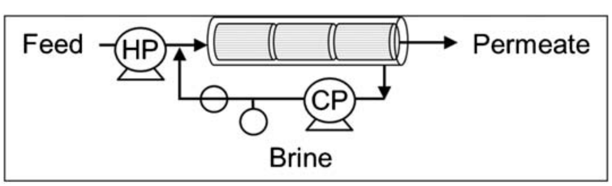
Batch RO has been described in the literature (Bratt, 1989; Szucz and Szucz, 1991). It is in wide use in laboratory settings where it has shown the potential to reduce the volume of concentrate produced during RO treatment with high concentrations of sparingly soluble salts without indications of membrane fouling or scale deposition (Tarquin and Delgado, 2012). However, the practical application of batch RO has been limited because of the higher energy requirements, higher capacity components and reduced permeate quality compared to continuous or PF systems.

The incorporation of the enormous benefits offered by batch RO for continuous desalination and water treatment was made possible by development of semibatch RO or closed circuit desalination (CCD) technology (Efraty *et al.*, 2011; Efraty and Gal, 2011; Efraty, 2012). Two configurations of the process have been developed, the first most suitable for higher salinity sources such as seawater (SWRO-CCD) and the second for lower salinity sources such as brackish desalination and industrial water treatment applications (BWRO-CCD) (Efraty, 2010a, b). The performance of semibatch processes can be modeled with standard membrane projection software. Good correlation between model membrane feed pressure and energy consumption and that measured in the field has been established (Stover and Efraty, 2011; Stover, 2012a, b).

The purpose of this paper is to analyze membrane performance in semibatch RO, specifically, energy consumption, overall flux and recovery of membrane arrays and of individual elements in multi-element arrays. Consideration is given to the costs, savings and benefits of this emerging technology.

Semibatch RO/NF process

A semibatch RO/NF process for high permeate recovery operation is illustrated in Fig. 1, with a single membrane pressure vessel representing multiple modules operating in parallel. A high pressure pump (HP) feeds a closed loop comprised of a single stage of membrane elements and a circulation pump. Permeate is produced at a rate equal to the flowrate of the HP. Brine is recirculated without depressurization. When a desired recovery percentage is reached, brine is throttled out of the system, displaced by feedwater from the HP in a single PF sweep. The exchange of brine and feedwater is executed without stopping the HP or the production of permeate. The process then returns to closed circuit operation, during which there is no brine reject stream. The initial pressure requirement of each sequence is proportional to the osmotic pressure of the feedwater and the maximum is proportional to the osmotic pressure of the final brine, the same pressure as the running pressure of a conventional RO stage. The resulting average membrane feed pressure in the semibatch RO process is much lower than the feed pressure of typical RO systems.



1 Semibatch RO/NF process schematic diagram

The overall recovery rate in a semibatch RO process is a function of the intrinsic volume of the system and the volume fed over the course of a sequence, the latter being flexible. Therefore, recovery is flexible and can be set at the system control panel. Being able to achieve high recovery in a single stage is a novel capability with beneficial implications for system cost and design and operational simplicity. It is not necessary to use multiple stages or six- to eight-element long membrane arrays to achieve high recovery as is necessary in conventional RO processes. A high recovery semibatch RO process can be constructed with just one membrane element, for example. More typically, semibatch RO membrane arrays of three or four elements have been found to optimally balance performance and costs (Stover, 2011). Two arrays can be housed in a single center port pressure vessel fed from both ends, with brine take-off from a center port. This center port configuration can result in fewer pressure vessels than are required for a comparable conventional RO process, reducing both footprint and capital cost.

Good resistance to fouling and scaling and high recovery operation are important in most brackish water desalination, industrial water treatment and water reuse applications. Semibatch RO systems provide new or enhanced means for addressing these challenges. Cross-flow supplied by a circulation pump washes the membranes and reduces the effects of scaling and fouling. As the salinity throughout the semibatch RO process cycles from that of the feedwater to that of the most concentrated brine, biofilm formation and scale precipitation can be disrupted.

Studies have shown that recovery rates that produce high degrees of supersaturation of sparingly soluble salts can be achieved in batch RO processes, even without the use of scale inhibitors. Specifically, recovery rates of over 90% have been achieved and maintained from water sources with high concentrations of silica and calcium sulfate, producing brine concentrations of these constituents that are four times higher than can be sustained in conventional RO processes. Furthermore, scale depositions can be dissolved by batch cycling, making sustained run times at high recovery rates possible even with source waters with high levels of sparingly

Table 1 Example calculations for semibatch RO for one complete sequence

Cycle	Flux/gfd	Feed flow	Permeate	Recovery	TDS in	TDS out	Feed P/psi	DP/psi	Average energy kWh kgal^{-1}	Average energy kWh m^{-3}
1	8·7	1030	412	40%	2901	4800	80	…	0·65	0·17
2	16·8	792	792	60%	3945	7153	135	15	1·38	0·37
3	16·8	792	792	70%	5239	9480	152	15	1·56	0·41
4	16·8	792	792	76%	6519	11 794	170	15	1·75	0·46
5	16·8	792	792	80%	7792	14 096	186	16	1·89	0·50
6	16·8	792	792	83%	9058	16 386	203	15	2·06	0·54
7	16·8	792	792	85%	10 317	18 663	220	15	2·23	0·59
8	16·8	792	792	86%	11 570	20 930	238	15	2·40	0·63
9	16·8	792	792	88%	12 816	23 183	255	15	2·58	0·68
10	16·8	792	792	89%	14 056	25 423	273	15	2·75	0·73
11	16·8	792	792	90%	15 288	27 651	290	15	2·92	0·77

soluble salts (Tarquin and Delgado, 2012). One explanation for the observed performance is that the cycle time of the batch RO process is much shorter than the induction time for precipitation of most sparingly soluble salts. This contrasts from conditions in conventional RO systems, in which constant concentrations are maintained throughout their membrane arrays for months or even years.

The scaling resistance benefits of batch RO operation are better exploited in semibatch RO processes because the intrinsic system volumes are typically much smaller and cycle times shorter. Also, because recovery can be easily manipulated, semibatch RO processes can be tuned to maximize recovery if the concentration of scaling salts or other feedwater properties allow this change.

Membrane design and performance modeling

The flowrates, pressures and energy requirements of semibatch RO system can be computed with an iterative application of standard projection software from membrane manufacturers (ROSA, 2010; IMS Design, 2011; Toray DS, 2011) and feedwater and pump information. The procedure is as follows:

(i) an initial membrane projection is run to simulate PF flushing of the membranes with fresh feed from the HP. HP flow produces both permeate flow and released brine flow. The HP speed can be increased to maintain any desired permeate flowrate during this step. The composition of the membrane feed during PF operation is that of the fresh feed

(ii) a membrane projection is run for the first closed circuit recirculation with the process configuration (typically three or four membranes per module). Permeate flow equals HP flow such that overall recovery is 100%. The membrane feed flow is the sum of the fresh feed flowrate and the recirculated flowrate and module recovery is typically 20–50%. The projection software report gives the membrane feed pressure, the membrane differential pressure, the brine composition and the flux and recovery of each individual membrane element

(iii) the composition of the membrane feed for the second recirculation is computed by combining the brine composition from the initial projection with the fresh feed composition at the ratio corresponding to the membrane (internal) recovery rate. The projection software is run a second time yielding a higher membrane feed pressure, a similar differential pressure, a new brine composition and the flux and recovery of each membrane element

(iv) step 3 is repeated for each additional recirculation necessary to achieve the desired overall recovery. Alternately, Step 2 can be applied to the last recirculation corresponding with the desired overall recovery

(v) energy consumption is computed with the permeate flow weighted average of the membrane feed pressures, the average of the membrane differential pressure, the pump flowrates and the pump and motor efficiencies.

Example calculations from a recently published paper are reproduced in Table 1 (Stover, 2012b). The first line in the table corresponds with the first step described above. These data show that the increase in brine TDS, membrane feed pressure and energy consumption with each cycle in the sequence is linear, while flux and membrane differential pressures are constant.

Case study

The energy requirements of a semibatch RO system and a conventional multistage BWRO system are considered for an example source water with the composition listed in Table 2.

Table 2 Case study: source water analysis

Ion	mg L^{-1}	Ion	mg L^{-1}	Ion	mg L^{-1}
Ca	33	Sr	3·1	NO_3	0
Mg	62·5	CO_3	0·1	B	0
Na	576	HCO_3	41	SiO_2	0
K	24·6	SO_4	203	CO_2	1·9
NH_4	0	Cl	980	TDS	1924
Ba	0	F	0·7	pH	7·5

Software from a commercial supplier of scale inhibitors (Avista, 1999) indicates that 97% recovery is possible with this source water without scale precipitation, without pH adjustment and with minimal antiscalant dosing. However, it should be noted that all currently published recovery rate and antiscalant dosing recommendations are

• Permeate flowrate	863 gpm/196 m^3 h^{-1}
• Overall recovery	88%
• Maximum element flux	18 gfd/30 lmh
• High pressure pump × motor efficiency	70%
• Booster/circulation pump efficiency	70%
• Membrane elements	Filmtec BW30-440i
• Membrane age	3 years

based on equilibrium saturation levels and do not take into account the kinetics of precipitation. This is appropriate for conventional RO processes in which brine/feed compositions are essentially constant, but in batch and semibatch processes, high concentrations of sparingly soluble salts in RO retentate are transient since they are replaced frequently with low concentration feed water. Generally, CCD systems allow for higher concentrations of sparingly soluble salts in the brine because these concentration levels exist only for an instant, therefore higher recovery rates can be achieved.

The following common assumptions were made for the model semibatch RO and conventional multistage BWRO systems,

The semibatch RO process consisted of 21 8M center port pressure vessels housing two four-membrane-element arrays in each for a total of 168 membrane elements at an average flux of 14 gallons per square foot of membrane surface per day (gfd) or 25 L per square meter per day (lmh). It was modeled as described above using software from a commercial supplier of RO membrane (ROSA, 2010).

The model results for the semibatch RO process were compared to those of a three-stage conventional RO system design which was modeled to the same recovery percentage and the same maximum element flux using the same projection software. The pressure vessel configuration in the conventional RO process was 16–8–4 of 7M pressure vessels housing a total of 196 membrane elements; the reduction in the number of vessels in each subsequent stage to help maintain sufficient cross-flow as permeate was removed. Permeate from the first two stages was throttled and the pressure of the feed to the last stage was boosted to balance flux along the stages, to prevent overflux of lead elements and to help maintain sufficient feed/brine cross-flow throughout the membrane array. A pump was selected as the interstage boosting device. Hydraulic turbochargers are available for this application, but they were not considered because greater operational flexibility is typically required than can be provided by these devices and because the hydraulic power demand by the fourth stage and the corresponding energy savings opportunity is minimal.

It is important to emphasize that the basis of comparison was the same recovery rate, the same permeate flowrate and the same maximum element flux. Processes with the same recovery rate and maximum element flux are considered to have similar fouling resistance and sustained performance. The number of membranes and the average fluxes used for modeling the compared processes were not equal. The reason that it was possible to use fewer membrane elements in the semibatch process but maintain the same maximum flux was that the shorter membrane arrays employed in the semibatch process provided better flux distribution.

Membrane projections for desalination of the source water were developed. Both the conventional and semibatch systems were modeled without warnings in the membrane projection reports. This is an indication that the membrane systems were designed in compliance with manufacturer's specifications and guidelines. It should be noted that the projections for the conventional RO process were difficult because of model instability. Specifically, flux balance and brine flows were very sensitive to changes in boost and throttle pressures of just a few psi, resulting in design warnings or alerts from the projection program. Membrane projection and power demand calculation results are summarized in Table 3.

These results show that the conventional RO process would require 20% more energy to produce the same amount of permeate at the same overall recovery rate, even though it was designed with 17% more membrane elements, 14% lower average flux and 33% more pressure vessels than the semibatch RO system.

The choice of 88% recovery for the semibatch process was arbitrary. Greater than 97% recovery is possible by control panel setting using the same equipment, cutting brine waste production by a factor of 4 or more. Over 97·3% recovery operation has been demonstrated in the field (Stover, 2011).

Conclusions

The data and analysis presented in this paper support the following conclusions:

- Maximum recovery: single stage semibatch RO processes can be designed to operate at 97% or higher recovery while maintaining compliance with membrane manufacturer's specifications. Recovery is adjustable over a wide range and automatically maintained by standard system controls.

Table 3 Case study: modeling results summary

	Pressure vessels	Membrane elements	Avg flux gfd (lmh)	Max flux gfd (lmh)	Avg pressure psi (bar)	Max pressure psi (bar)	Average specific energy kWh/1000 gal (kWh m^{-3})
Conventional	28	196	14 (25)	18 (30)	265 (18)	265 (18)	3·0 (0·80)
Semibatch	21	168	17 (29)	18 (30)	201 (14)	285 (20)	2·5 (0·67)

- Flexibility: high operational flexibility including adjustable recovery and adjustable cross-flow, set at the control panel, are inherent features of semibatch RO processes.
- Energy consumption: performance modeling indicates that semibatch RO processes can consume less energy than comparable conventional BWRO processes.
- Process stability and reliability: single stage semibatch RO systems are relatively easy to design and model. Flux and cross-flow can be adjusted independently making process design models more stable than those for conventional multistage conventional RO processes, and this bodes well for the reliability and stability of installed semibatch RO systems. Salinity cycling and adjustable high cross-flow help disrupt and reduce the effects of fouling and scaling, contributing to process reliability and reducing costs.
- Capital cost: a semibatch RO process can be designed with fewer membrane elements and pressure vessels than a comparable conventional BWRO process, reducing capital cost while still saving energy. For the same reasons, the semibatch RO process is also effective in reducing footprint.

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