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Industrial and brackish water treatment with closed circuit reverse osmosis

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ABSTRACT

Closed Circuit Desalination (CCD™) technology is an emerging platform for reverse osmosis (RO) water treatment and desalination. It lowers the feed pressure requirement, improves the membrane performance, increases the operational flexibility, and eliminates the need for energy recovery devices using only standard RO equipment. For industrial water treatment and brackish water desalination applications, CCD technology achieves maximum recovery in single-stage units while saving energy. Alternately, a CCD unit can be added to a conventional RO process to concentrate brine and raise recovery. Over 97% recovery has been demonstrated in a single-stage operation. The recovery rate of a CCD unit can be adjusted at the control panel without modification of system hardware, limited only by the scaling characteristics of the feedwater. Maximum recovery operation and high flexibility have significant cost-cutting implications for industrial water treatment and inland brackish desalination, where both feedwater supply costs and brine disposal fees can be significant. CCD systems also demonstrate excellent resistance to fouling and scaling. Cross-flow supplied by a circulation pump washes the membranes, and salinity cycling disrupts and greatly reduces the scaling and fouling. Short membrane arrays and high cross-flow allow the CCD process to operate at higher average fluxes than conventional RO processes, without exceeding the membrane manufacturer's flow or recovery specifications. This paper describes the design and modeling of high-recovery CCD processes and compares the measured and calculated specific energy consumption levels to validate modeling methods and tools. Two brackish water RO cases are considered: one using Desalitech's seawater reverse osmosis–CCD (SWRO-CCD) process and the other using its hybrid plug flow desalination–SWRO–CCD (PFD-SWRO-CCD) process. CCD systems are compared favorably to conventional RO trains modeled with the same feedwater, high-pressure pumps, and membranes operating at the same average flux and overall recovery percentage.

Keywords: Industrial; Brackish; Closed circuit; Reverse osmosis

1. Introduction

Closed Circuit Desalination (CCD) technology is emerging as a broadly applicable advanced reverse osmosis (RO) process for water purification in brackish and seawater desalination, wastewater treatment and reuse, and water purification applications [1–5]. The same tools used to design conventional RO systems are used to design CCD systems, namely membrane manufacturer's projection models, mem-

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012,Barcelona, Spain brane and pump specifications, and other generally available mechanical engineering data, resources, and methods. Rarely is it possible to operate two different RO technologies under the same conditions to compare their performance. However, it is possible to conduct an ideal A-B comparison of alternative process designs or components, or to consider performance over a wide range of feedwater properties or operating conditions in a paper study using RO design tools and models. Clearly, it is important that the models used for such exercises accurately fit field data.

2. SWRO-CCD process design and modeling

The SWRO-CCD process 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 membranes and a circulation pump (CP). Permeate is produced at a rate equal to the flow rate of the HP. Brine is recirculated in batch-like operation. When a desired recovery level is reached, brine is displaced with feed water from a hydrostatically pre-pressurized side chamber. The exchange of brine and feedwater is executed without stopping the HP, the CP, or the production of permeate. The initial membrane feed pressure of each CCD sequence is just above the osmotic pressure of the feedwater and the maximum pressure is just above the osmotic pressure of the final brine, resulting in an average membrane feed pressure that is much lower than the feed pressure of typical RO systems.

The flow rates, pressures, and energy requirements of a CCD system can be computed with an iterative application of standard projection software from membrane manufacturers [6–8] and feedwater and pump information. The procedure is as follows:

(1) A membrane projection is run for the first CCD recirculation with the process configuration (typically three or four membranes per module) and the desired flow rate and module recovery rate. Module recovery is typically 20–50%—much lower than the overall recovery rate in most brackish and industrial water applications. The projection software outputs include the membrane feed pressure, the membrane differential pressure, and the brine composition.

(2) The composition of the membrane feed in 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 recovery rate. The projection software is run a second time yielding a higher membrane feed pressure, a similar differential pressure, and a new brine composition.

(3) Step 2 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.

(4) Energy consumption is computed with the average of the membrane feed pressures, the average of the membrane differential pressures, the pump flow rates, and the pump and motor efficiencies. The calculation also gives the pump duties and permeate quality.

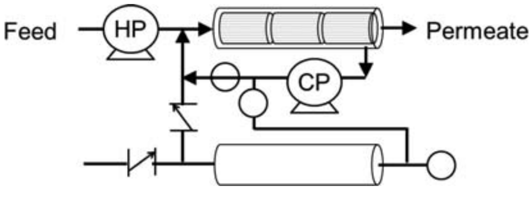

Fig. 1. SWRO-CCD process schematic diagram.

3. SWRO-CCD and conventional RO process performance

A SWRO-CCD process is being applied as a commercial installation at the Kibbutz Reim site in Israel to desalinate brackish ground water for agricultural use. The unit produces up to 835 m^3 of permeate per day and has operated continuously with greater than 98% availability since February 2009, the rare downtime being mostly associated with power outages. The feed source has variable salinity, ranging from 5,600 to 9,000 μS/cm. It contains domestic effluents and other challenging constituents, but was operated without media filtration for about two years with minimal clean-in-place operations. Details of the design and performance of the unit are given in Ref. [2]. Photographs of the unit are reproduced in Fig. 2. The water composition for the field trial of interest is given in Table 1.

A conventional RO system operating on the same feedwater to the same recovery percentage would require three stages. To balance the flux of the three stages and thereby prevent excessive fouling of the head/lead membrane elements, permeate throttling and/or interstage pressure boosting would be required. The maximum head element flux in all of the process configurations considered was 34 liters per square meter per hour (lmh) or 21.3 gallons per square foot per day (gfd) in accordance with the maximum estimated head element flux in the CCD field installation.

Fig. 2. 835 m^3/day Reim SWRO-CCD unit.

Table 1
Feed water composition for Reim SWRO-CCD process field trial

Ion	mg/l	Ion	mg/l	Ion	mg/l
Ca	164	CO_3	0.5	SiO_2	6.0
Mg	75	HCO_3	318	CO_2	31
Na	585	SO_4	298	TDS	2,455
K	10	Cl	982	pH	7.2
NH_4	0.0	F	1.0		
Ba	0.0	NO_3	14	Turbidity	0.7 NTU
Sr	0.0	B	1.0		

Field test results [2], CCD modeling results, and the predicted performance of three-stage conventional RO systems with permeate throttling on the first and second stages or permeate throttling on the first stage and a booster pump feeding the third stage are given in Table 2. RO energy consumption was computed exclusive of the listed feedwater supply pressure.

These data show excellent correlation between measured and modeled SWRO-CCD system specific energy consumption, flows, and pressures. The data also show that a conventional RO system with permeate throttling would consume 56% more energy as the running CCD system and a conventional system with an interstage booster pump would consume 22% more.

4. Hybrid PFD-CCD and conventional RO process descriptions and performance

The hybrid PFD-CCD process is comprised of a conventional RO (PFD) stage feeding a SWRO-CCD system. The CCD system side conduit can be fed either pressurized brine from the PFD stage or, in the case considered here, low-pressure feedwater. Therefore, the CCD unit functions as a brine concentrator. A process configured in this manner can be implemented as a retrofit of an existing RO process, requiring almost no modification of the original RO system.

A 1,320 m^3/day hybrid PFD-CCD unit is being operated as a commercial installation and used to desalinate brackish water at the Maagan Michael site in Israel. Like the Reim source water, the Maagan source water has variable salinity and is laden with foulants that have proven problematic for conventional RO systems fed from the same source. The PFD stage is equipped with 400 ft^2 membrane elements, and the CCD stage has 440 ft^2 membrane elements. Details of the unit and its performance are given in Ref. [3]. For comparison, the first stage of the hypothetical conventional RO system was modeled with 400 ft^2 membrane elements and the second and third stages with 440 ft^2 elements. The feedwater has the composition listed in Table 3.

Table 2
Field and model data for SWRO-CCD and conventional RO processes

	SWRO-CCD measured performance	SWRO-CCD model	Conventional RO model, 3-stage, permeate throttled	Conventional RO model, 3 stage, inter-stage boost
Membrane type	ESPA2 MAX	ESPA2 MAX	ESPA2 MAX	ESPA2 MAX
Permeate flow, m^3/h	35.0	35.0	35.0	35.0
Recovery	88%	88%	88%	88%
Overall average flux, lmh	26.8	26.8	26.8	26.8
Supply pressure, bar	2.0	2.0	2.0	2.0
First stage fresh feed flow, m^3/h	35.0	35.0	39.8	39.8
First stage membrane feed, m^3/h	70.8	70.8	39.8	39.8
First stage module recovery	49%	49%	51%	51%
First stage permeate flow, m^3/h	35.0	35.0	20.2	20.2
First stage brine flow, m^3/h	35.8	35.8	19.6	19.6
First stage brine pressure, bar	11.1	9.9	20.7	14.5
First cycle feed pressure, bar	12.0	11.3	–	–
Last cycle feed pressure, bar	20.0	19.4	–	–
Average feed pressure, bar	16.0	15.4	22.8	16.6
Differential pressure, bar	0.92	1.4	1.1	2.1
First stage average flux, lmh	26.8	26.8	27.4	27.4
Second stage boost pressure, bar	–	–	–	0.0
Second stage feed pressure, bar	–	–	20.5	14.5
Second stage brine flow, m^3/h	–	–	8.8	8.8
Second stage average flux, lmh	–	–	26.3	26.4
Second stage recovery	–	–	55%	55%
Third stage boost pressure, bar	–	–	–	6.2
Third stage feed pressure, bar	–	–	19.2	19.1
Third stage average flux, lmh	–	–	24.8	24.7
Third stage recovery	–	–	47%	45%
HP pump efficiency	55%	55%	55%	55%
CP pump efficiency	45%	45%	–	45%
Specific energy, kWh/m^3	0.77	0.76	1.19	0.93

Table 3
Feed water composition for Maagan Michael hybrid SWRO-CCD process

Ion	mg/l	Ion	mg/l	Ion	mg/l
NH_4	2.0	Ba	0.1	SiO_2	0.0
K	42	HCO_3	290	CO_2	34.9
Na	1,038	NO_3	0.0	CO_3	0.4
Mg	138	Cl	2,011	pH	7.00
Ca	182	F	0.0	TDS	3,965
Sr	2.0	Boron	0.4		
Fe	0.0	SO_4	259		

A conventional RO system extracting the same percentage of permeate from the same feedwater would require three stages. To balance the flux in the model, permeate from the first and second stage was throttled or, alternately, permeate from the first stage was throttled and a booster pump was used between the second and third stages. Maximum head element flux was limited to 33 lmh (20.6 gfd).

Field test results [3], CCD modeling results, and the predicted performance of the two alternative conventional RO systems are given in Table 4. The reported energy consumption values are exclusive of the feedwater supply pressures listed in Table 4.

These data show good correlation between measured and modeled SWRO-CCD system specific energy consumption to within 6% with lower energy consumption by the installed system. The data also show that a conventional RO system with permeate throttling would consume twice as much energy as the running CCD system and a conventional system with an interstage booster pump would consume 41% more.

Note that the combined efficiency of the CP and motor in the actual CCD system was very low—just 30%—indicating that this pump was not correctly sized for this application. Nevertheless, the same pump efficiency was assumed in the model CCD system. If the efficiency of the CP and motor was a more typical 60%, CCD system specific energy consumption would be reduced by about 2% from the values indicated in Table 4. In the model of the conventional RO system with an interstage booster pump, a pump efficiency of 60% was assumed. If, instead, a 30% efficient interstage booster pump was considered or if the efficiency of the pump dropped from 60 to 30% because the pump's duty point shifted away from its best efficiency point, specific energy consumption of the conventional RO system would be 0.92 kWh/m^3 or 11% higher than predicted in Table 4. These considerations illustrate that energy consumption in multistage conventional RO systems is much more sensitive to changes in system operating conditions or feedwater properties than comparable CCD processes.

5. Discussion and conclusions

Field performance and the above analysis support the following observations and conclusions:

- CCD system energy consumption and pump sizing can be accurately modeled with an iterative application of membrane projection models and standard mechanical engineering calculations as validated by comparing measured performance in commercial installations. This modeling approach can, therefore, be used to compare the performance and equipment requirements of CCD and conventional RO systems for a broad range of water compositions and with a broad range of membrane and pump models.
- The analysis included a single-stage SWRO-CCD unit operating at over 88% recovery. Field tests with CCD technology have demonstrated that over 97% recovery is achievable.
- The CCD systems considered are projected to consume significantly less energy than conventional RO systems built with the same membranes and HPs operating at the same flux and recovery.
- CCD systems are more flexible than multistage conventional RO systems in the face of changing operating conditions or feed water properties because recovery, cross-flow, and flux can be independently and even automatically manipulated with control panel set points.
- The two field-installed CCD systems have proven to be highly reliable treating difficult sourcewaters that would likely foul the membranes in

Table 4
Field and model data for hybrid SWRO-CCD and conventional RO processes

	SWRO-CCD measured performance	SWRO-CCD model	Conventional RO model, 3-stage, permeate throttled	Conventional RO model, 3 stage, inter-stage boost
Membrane type	RE8040-BE400/440	RE8040-BE400/440	RE8040-BE400/440	RE8040-BE400/440
Permeate flow, m^3/h	55.0	55.0	55.0	55.0
Overall recovery	88.5%	88.5%	88.5%	88.5%
Average flux, lmh	18.3	18.3	18.3	18.3
Supply pressure, bar	2.5	2.5	2.5	2.5
First stage feed pressure, bar	10.5	11.9	25.8	16.7
First stage feed flow, m^3/h	55.0	55.0	62.2	62.2
First stage brine flow, m^3/h	27.5	27.5	29.5	25.7
First stage brine pressure, bar	9.2	10.6	25.2	16.1
First stage average flux, lmh	–	24.7	18.3	20.4
First stage recovery	50%	50%	52%	59%
First cycle feed pressure, bar	12.0	11.1	–	–
Last cycle feed pressure, bar	27.0	29.1	–	–
Average feed pressure, bar	19.5	20.1	–	–
Differential pressure, bar	0.45	0.2	0.6	0.6
Second stage feed pressure, bar	–	–	25.2	16.1
Second stage brine flow, m^3/h	30.0	30.0	14.6	11.9
Second stage average flux, lmh	–	14.0	18.2	16.9
Second stage recovery	79%	79%	51%	54%
Third stage boost pressure, bar	–	–	–	9.0
Third stage feed pressure, bar	–	–	24.8	24.5
Third stage average flux, lmh	–	–	18.3	11.6
Third stage recovery	–	–	51%	40%
HP pump efficiency	72%	72%	72%	72%
CP/BP pump efficiency	30%	30%	–	60%
Specific energy, kWh/m^3	0.59	0.63	1.21	0.83

conventional RO processes. This excellent performance derives from the short membrane arrays, relatively high cross-flow and low module recovery rates utilized in CCD process designs. In addition, the salinity cycling inherent in the semi-batch operation of CCD systems tends to disrupt biofilm formation and scale precipitation.

- The SWRO-CCD process can be deployed for new builds or as retrofits of existing conventional RO systems to raise overall recovery, reduce specific energy consumption, and improve RO process reliability.

The water compositions, recovery rates, and fluxes chosen for this analysis were arbitrary. Field operation of the CCD systems described herein has confirmed that the recovery rate of any CCD unit can be adjusted at the control panel with the installed pumps and without modification of system hardware. Maximum recovery operation and high flexibility have significant cost-cutting implications for industrial water treatment and inland brackish desalination, where feedwater compositon can vary and where both feedwater supply costs and brine disposal fees can be significant.

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