Since the inception of reverse osmosis (RO) for desalination in the late 1950s, basic membrane desalination processes have remained essentially unchanged, despite improved membranes and energy recovery devices. Conventional RO is a hydrodynamic plug-flow process with pressurized feed to semipermeable membranes split into two outlet streams—one of pressurized brine and the other of unpressurized permeate. The energy that remains in the pressurized brine stream must be recovered with energy recovery devices or lost across a brine valve. A new desalination technique—a continuous closed-circuit desalination (CCD) process—operates on the basis of relatively low average feed pressures and other operating advantages of batch RO with the continuous flow rates of feed and permeate of conventional RO. This article provides an overview of the CCD process, presents experimental data from operating CCD processes, and establishes the principles on which the technology can be applied to satisfy a wide range of desalination requirements.

Low-Energy Consumption With Closed-Circuit Desalination

By Richard L. Stover and Nadav Efraty

Closed-circuit desalination (CCD) (Efraty 2009 and 2010) technology has been demonstrated in continuous operation on Mediterranean Sea water with 40–50 percent recovery, 8–26 L/m^2/hour (lmh) flux and reverse osmosis (RO) energy consumption in the range of 1.7–2.6 kW·h/m^3 of permeate (Efraty et al, 2010; Efraty et al, 2011a and 2011b; Efraty, 2011). The same system operating in ocean water at typical flux and recovery rates can be expected to consume less than 1.5 kW·h/m^3, a major reduction in energy consumption compared with the most advanced conventional seawater RO (SWRO).

Alternately, a CCD unit can be operated at energy consumption rates comparable to conventional RO systems but at demonstrated fluxes of up to 39 lmh (24 gfd) in seawater. Applying CCD technology in this manner reduces the number of membrane elements required, as well as the associated footprint and capital costs. High flux is achieved without exceeding membrane capacity, particularly because of use of short membrane arrays and application of high cross flows. CCD technology's application also has been demonstrated in brackish water with low energy consumption, high recovery, and good resistance to fouling and scaling in processes operating continuously for more than 3 years. The CCD process is applicable at any scale, from small RO systems operating with a single membrane element to large mega-plants.

In RO processes, feed is split into brine and permeate. Energy required for the separation process consists of

- osmotic energy, which corresponds to the osmotic pressure requirement that must be met by the high-pressure pump and is a function of the composition and physical properties of the brine.
- net-driving energy, which is the high-pressure pump energy necessary to create permeate flow and is a function of membrane permeability, concentration polarization, and any pressure that remains in the permeate.
- recirculation energy, which is consumed by the pump that recirculates brine, if used.
- reject energy, which leaves the process in the brine stream.

Since CCD's initial demonstration in the 1960s (Loeb and Sourirajan, 1963), major reductions in RO energy consumption have been achieved with membrane and pump-efficiency improvements and use of energy recovery devices (ERDs) (Stover, 2009). Improved membranes increase permeability and reduce the net-driving pressure (NDP) required. Turbine-based ERDs reduce energy lost in the membrane reject stream by returning a large portion of its energy to the high-pressure stream that feeds the process. Isobaric ERDs further reduce reject waste energy by returning more energy contained in the brine stream to the membrane feed. However, until now, improvements made to conventional RO processes have not directly reduced osmotic energy or substantially eliminated reject losses.

The CCD process resolves batch RO's shortcomings and makes the operation continuous and applicable for commercial use.

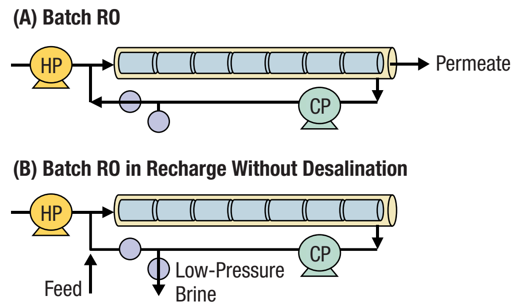
RO Processes

Before detailing the CCD process, it is important to establish the context of conventional and batch RO.

Conventional RO. Conventional RO is a continuous process in which a pressurized feed stream (Q_F) directed to membrane modules is split into pressurized brine and depressurized permeate (Q_P). Overall system recovery—the ratio of Q_P over Q_F—is a function of the number of membrane elements in series through which the feed passes, with feed-flow and recovery rate limitations imposed by each membrane element. The feed pressure in conventional RO corresponds to the osmotic pressure of the brine plus NDP and pressure drop from the head to the tail membrane. Operation is typically "plug flow," with a single pass of feedwater in a given stage and a continuous release of pressurized brine. The energy contained in the brine can be boosted for additional desalination in a second stage, recovered with an ERD, or wasted across a brine valve.

Batch RO. In addition to conventional RO, a relatively unknown class of batch RO processes has also been described in patent literature (Bratt, 1989; Szucz and Szucz, 1991). The typical apparatus for batch RO, illustrated in Figure 1, consists of a pressure vessel with one or more membrane elements inside, a feed pressurizing pump (HP), a circulation pump (CP) for concentrate recycling from outlet to inlet of the module(s), and valves to enable brine replacement with fresh feedwater when batch desalination is completed. The batch RO process operates on the basis of hydrostatic principles, i.e., feed and permeate flow rates are equal. Cross flow over the membranes is created by a CP. Batch RO occurs only in the presence of concentrate recycling, without which desalination ceases because of an immediate rise in concentration polarization. With concentrate recycling, desired cross-flow conditions may be attained independently of the overall recovery rate. Brine is recirculated until the desired recovery rate is achieved, as illustrated in Figure 1A. HP flow and permeate production are halted while the system is hydrostatically depressurized and brine is displaced with fresh feedwater at atmospheric pressure, as illustrated in Figure 1B. The pumps are then restarted, and the system is pressurized and returned to the state illustrated in Figure 1A.

Figure 1. Typical batch RO apparatus



HP = Feed Pressurizing Pump
CP = Circulation Pump

The overall permeate recovery rate (R) is the ratio of permeate flow to feed flow, including the feed used to initially fill the system. Membrane or module recovery (MR) is the ratio of permeate flow rate to membrane feed flow rate. R and MR are equal in a conventional RO process but differ in a batch RO process. Recirculation flow and permeate flow are controlled by different pumps. R and MR are related according to the following equation, which reduces to R = MR in a conventional plug flow system where S = 1:

Equation 1

$$MR = \frac{1}{[S \times (1/R - 1) + 1]}$$

Where:
S = the number of membrane passes per batch cycle

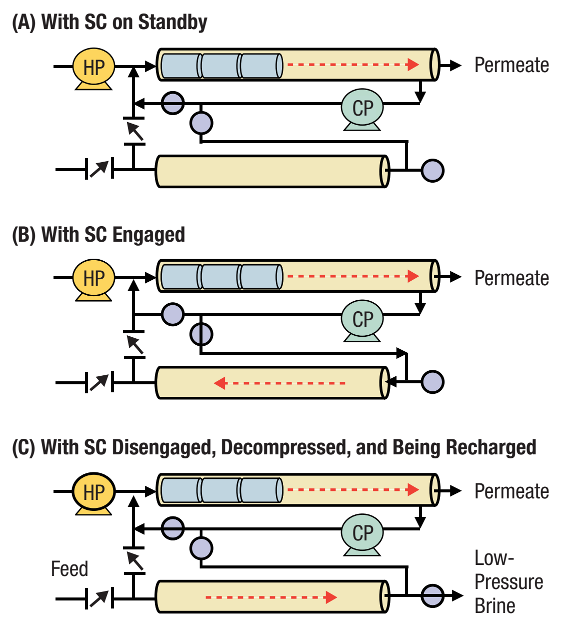
Like conventional RO, the feed pressure required for batch RO corresponds to the osmotic pressure of the brine plus NDP and the differential pressure drop (DP) in the brine channel. However, osmotic pressure in a batch process is initially that of fresh feed and reaches a level corresponding to the final brine concentration only at the end of the batch cycle. Inversely proportional to the membrane recovery rate, DP must be overcome with a circulation pump. The only energy lost in the process is from decompression of what remains at the end of the pressurization stage, an amount that is essentially negligible. As a result, an ERD is not required in batch RO, and average energy consumption in a batch RO process is less than in a conventional RO process of the same size. However, the discontinuous nature of a batch process increases required system capacity and associated capital costs and presents operational challenges. Therefore, batch RO has not been implemented in full-size commercial RO systems.

The CCD process resolves batch RO's shortcomings and makes the operation continuous and applicable for commercial use.

CCD

Incorporating batch RO's enormous benefits into continuous desalination was made possible by CCD technology. The process can be equipped with or without side

Figure 2. CCD membrane modules



conduits (SCs). Operating with SCs is most suitable for SWRO-CCD (Efraty, 2009), and operating without SCs is most suitable for brackish water desalination (BWRO-CCD) and industrial water treatment applications (Efraty, 2010).

BWRO-CCD. The BWRO-CCD process design is essentially the same as the batch RO process displayed in Figure 1, with modifications to enable a two-step consecutive sequential desalination process. Most of the time (85–90 percent), 100 percent recovery is experienced; 40–50 percent recovery plug-flow desalination is experienced the rest of the operating time (10–15 percent) while brine is replaced with fresh feed. The CCD step in the process takes place with a fixed flow for the HP under variable pressure conditions and fixed flow for the CP. Brine replacement is initiated when maximum applied pressure, maximum electric conductivity (EC) of the recycled brine, or a volumetric set point has been reached. Brine replacement is complete when a fixed volume of the closed circuit (CC) is filled with fresh feedwater. This can be controlled volumetrically by concentrate conductivity or elapsed time. Brine is completely flushed from the process at the end of each sequence. The duration of the sequence is much shorter than the induction time for most sparingly soluble salts, providing a a degress of scaling resistance.

As in the batch RO process, overall recovery is the ratio of the permeate flow rate to the system feed-flow rate, including the feed flow used to replace the brine, in proportion to the duration of the CCD step, which, in turn, is proportional to the volume of circuit, CP flow rate, and number of pressure vessel membranes. Overall recovery can be easily altered in the BWRO-CCD process by changing the duration of the CCD step. The module recovery rate is related to the overall recovery rate and number of recirculation passes according to Equation 1.

SWRO-CCD. Continuous CCD or SWRO-CCD operates similarly to batch RO and BWRO-CCD, i.e., at an osmotic pressure that ramps from that of the feedwater to that of the brine over the course of a cycle. However, the brine is replaced without halting or reducing permeate flow. As a result, continuous CCD achieves the same low, average energy consumption level of batch RO but with the continuous feed flow and permeate flow of conventional RO.

The SWRO-CCD process, illustrated in Figure 2, consists of a pressure vessel with one or more membrane elements, an HP, a CP for concentrate recycling from outlet to inlet of the membrane module(s) and for pressure difference compensation, an SC of the same volume as the principle CC, and valves to enable engagement and disengagement between the CC and SC.

The system's primary operational steps, as depicted in Figure 2, are:

- A: Desalination with a disengaged SC on stand-by filled with pressurized fresh feed
- B: Desalination with an engaged SC
- C: Desalination with a disengaged and decompressed SC being recharged with fresh feed.

The SC is then sealed, compressed, and left on stand-by for the next cycle. The SWRO-CCD process operates without need for energy recovery, because the main CC is constantly pressurized and compression of the SC, which occurs only at the end of the cycle, involves the loss of negligible amounts of hydrostatic energy. The continuous SWRO-CCD process is performed under variable pressure conditions in which there are fixed flow rates for the HP and CP. The engagement of the SC is initiated by reaching the desired maximum applied pressure or brine conductivity set point, and the disengagement of the SC is determined volumetrically or by conductivity signal.

As shown in Figure 2, membrane modules in the CCD process are usually only partially filled with membranes and the remaining module capacity is left empty. Full-length membrane pressure vessels are insignificantly more expensive than shorter pressure vessels, and the extra capacity provides sufficient volume in the CC to allow optimal sequence durations between SC engagements. Typically, three or four membrane elements are fitted into six- to eight-element pressure vessels, but full recovery can be achieved with as few as one element per vessel.

A primary energy-saving benefit of the CCD process, compared with conventional RO, is reduced average osmotic energy.

Like batch RO and BWRO-CCD processes, the recovery rate in the SWRO-CCD process is established by the duration of CCD and can be controlled by altering the maximum pressure or maximum brine conductivity set point. Module recovery is related to overall recovery and the number of recirculation passes according to Equation 1.

Benefits. A primary energy-saving benefit of the CCD process, compared with conventional RO, is reduced average osmotic energy. Another benefit is a reduction in pressure losses through elimination of the pressurized brine stream. The volume of water necessary to compress or decompress the CC is just a few tenths of a percentage of total system volume. In large systems, pumping of only a few centiliters of water is necessary to create the static pressure required for optimal permeate production. Although modern ERDs can recover more than 90 percent of the energy in the brine stream, there is an implicit loss of up to 10 percent, including pressure drops, internal leakage, mixing, overflush, and backpressure requirements (Stover and Andrews, 2011), that can be avoided in the CCD process.

It is important to note distinctions between the SC in the CCD process and isobaric ERDs, such as a pressure exchanger[1] and work exchanger[2]. SC provides some of the same functions in the CCD process that ERDs provide for conventional RO process. Namely, they accumulate pressurized feedwater for injection into the membrane array by a CP, and they accumulate depressurized brine for rejection from the RO unit by the supply pump. However, because flow and pressurization/depressurization occur at different times in the SC, it cannot be correctly described or treated as a work exchanger or ERD. The relaxed timing of SC engagement, which happens once every few CCD cycles, eliminates the need for robust, finely tuned valve operations and flow controls that enable modern isobaric ERDs.

In addition, far fewer valve actuations are required in the CCD process. Specifically, a maximum of five full-size valves are required per RO train, and each is opened and closed once during the CCD sequence—about 8 minutes in seawater systems. In contrast, a minimum of six valves is used to fill and discharge a work-exchanger ERD; they operate at least four times per minute, and a minimum of three ERDs are usually required per RO train. Therefore, the ratio of valve actuations in conventional RO to that in a CCD process is at least 115:1. Although a pressure-exchanger ERD nominally contains no valves, sealing surfaces inside each device operate at up to 100 times/second, and multiple devices are typically required.

The CCD process also provides important additional benefits. In contrast to conventional RO, wherein recovery is a function of the number of membrane elements in sequence, CCD recovery is a function of only the batch duration, irrespective of the number of elements per module. Therefore, recovery can be adjusted to sustain optimal system performance in response to feedwater and membrane condition changes, and high recovery levels may be attained. Cross flow is delivered by the circulation pump at a rate independent of the fresh feed/permeate flow rate. Because there are low pressure losses in the CC loop, the circulation pump requires little energy. Fewer membrane elements in series in the CCD process allow a more even flux distribution along the array, compared with long configurations in conventional RO. High cross flow can be applied to reduce concentration polarization and allow high flux while maintaining compliance with membrane specifications.

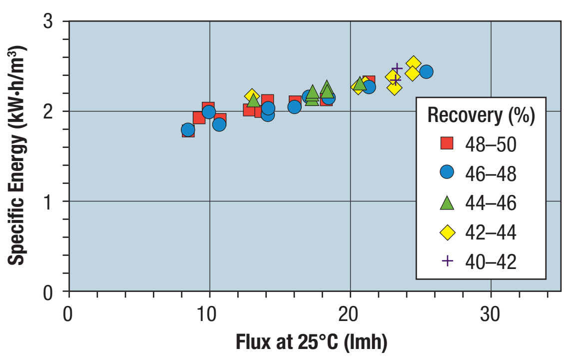
Similar considerations allow the membrane system to be operated without a high-pressure control valve at the discharge of the high-pressure pump, a device that wastes energy but is necessary in many conventional RO processes to limit flux through new membranes and to retain pump capacity for when membranes age or foul. Together with high cross flow, constant variation in feed salinity through the CCD operational cycles inherently inhibits biological fouling and scaling. This, in turn, may reduce pretreatment and chemical consumption requirements. Finally, the CCD process can be instantaneously stopped or started, as dictated by changes in electricity demand or availability. For this reason, the CCD process is well suited for use with discontinuous power supplies, such as renewable energy sources (wind, wave, and solar).

Field Trials

BWRO-CCD. BWRO-CCD technology was demonstrated successfully in two commercial units of up to 40 m^3/hour permeate production capacity (Efraty, 2011). Single-stage BWRO-CCD units were operated at recovery rates of up to 93.5 percent with a feed source of 600 ppm total dissolved solids (TDS), 90 percent with a feed source of 2,500 ppm TDS, 87 percent with a feed source of 5,700 ppm TDS, and 97.4 percent in a second-pass RO application. BWRO-CCD technology allows high recovery without multiple stages and has low energy requirements and installation/maintenance costs. Operation has been continuous since late 2009.

SWRO-CCD. Use of SWRO-CCD technology has been demonstrated for treating high-salinity brackish water in a commercial installation operating continuously since February 2009 (Efraty, 2011) with only a cartridge filter for pretreatment. The process has been validated by trials in seawater with 10 m^3/hour permeate production

Figure 3. Field trials: CCD–RO process specific energy vs. normalized flux



capacity, comprised of four modules with up to four membrane elements each, operating since February 2010 (Efraty et al, 2010; Efraty et al, 2011a and 2011b). The continuously monitored data included flow and EC of the feed, permeate, and recycled concentrate; pressure at the modules' inlet and outlet; feed and permeate pH; and each pump's individual energy consumption.

Desalination of Mediterranean Sea feedwater—with average salinity of 4.1 percent, temperature range of 22–32°C, multimedia filtration pretreatment, 40–50 percent overall recovery, and 7.0+0.5 percent head-element recovery—required specific energy in the range of 1.7–2.6 kW·h/m^3 in the respective flux range of 8–26 lmh, as shown in Figure 3. These data include energy requirements of only high-pressure and CPs. Pump motor energy consumption and pump output were measured directly in

Figure 4. Flow conditions

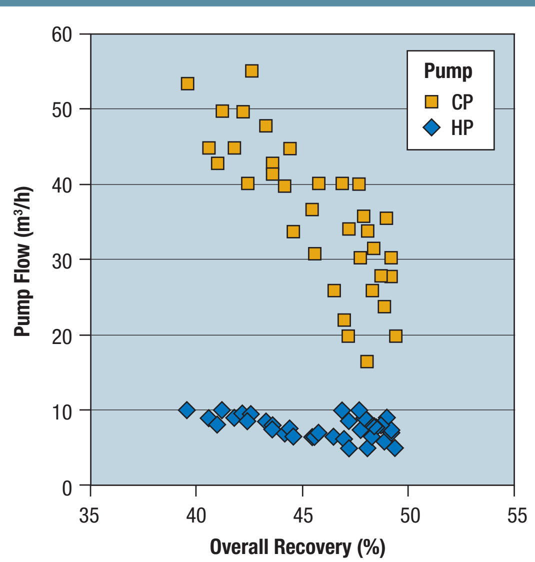
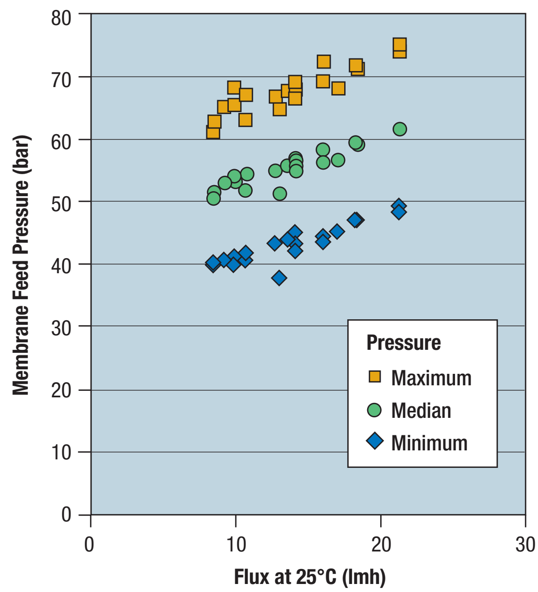


Figure 5. Pressure conditions



the CCD process, allowing CP efficiency to be calculated at 16–47 percent over the range of flows studied. In addition to its poor efficiency, the CP leaked substantially, adding duty to the high-pressure pump.

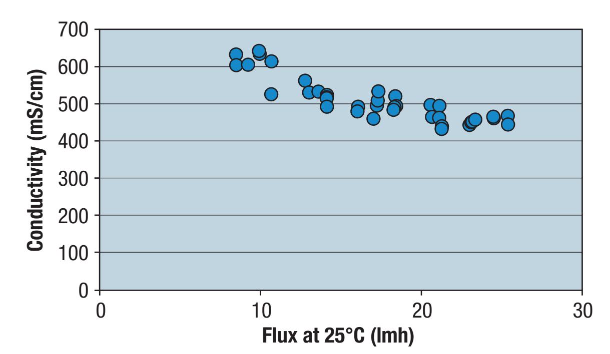
Data in Figure 3 indicate that the specific energy consumption gradually increased with increased flux; however, recovery had little influence on RO-specific energy requirements in the range of 40–50 percent. Specific energy consumption levels shown in Figure 3 are low compared with conventional RO, despite the system's small scale and poor CP performance.

Additional noteworthy information includes flow conditions (Figure 4), pressure conditions (Figure 5), and average permeate quality (Figure 6). The scatter in the flow data (Figure 4) stems from changes in the number of membrane elements (2–4 elements per pressure vessel) and recirculation passes that were made to achieve the desired flux range in the test system. During the CCD sequence, permeate salinity usually increases in direct proportion to salinity in the CC. Average permeate salinities from the CCD process are comparable to average salinities from conventional RO processes with the same membranes operating at the same recovery rate and flux. However, high-flux operation enabled by the CCD process reduces permeate salinity.

Low recovery (35–38 percent) and low flux (7–8 lmh) SWRO-CCD trials of Mediterranean Sea feedwater performed with consecutive sequential pressure variations of 38.2–50.5 bar demonstrated an exceptionally low RO

With elimination of ERD arrays, the number of moving components in large RO trains can be reduced significantly.

Figure 6. Average permeate quality vs. normalized flux



energy requirement (less than 1.6 kW·h/m^3), which is unattainable by conventional RO. High flux trials (as high as 40 lmh) and high recovery trials (53 percent recovery) were also tested without exceeding membrane manufacturer's specifications for head element recovery. In addition, these trials showed no performance losses resulting from fouling or scaling.

Performance Analysis

An energy consumption model for the CCD process was developed. Test data were re-evaluated considering more typical circulation pump performance. The model and test data were compared to establish correlation, validating the model as a way to extrapolate test data to other CCD systems and feedwaters.

Modeling Methodology. Energy consumption requirements of the core RO process of a CCD system can be predicted with an iterative calculation using standard projection software from membrane manufacturers[3,4] and pump, membrane, and feedwater information. The computational procedure is as follows.

1. A membrane projection is run assuming conventional plug-flow desalination with the CCD membrane configuration (typically 2–4 membranes per module) and the desired membrane recovery rate. Equation 1 is used to calculate the desired overall recovery rate and number of recirculation/membrane passes. The resulting report provides membrane feed pressure, membrane differential pressure, permeate quality, and brine composition from the initial membrane pass.
2. Feed composition for the second membrane pass is computed by combining the brine composition from the initial projection with the fresh feed composition at the appropriate ratio, dictated by the module recovery rate.
3. The projection software is run a second time, yielding a higher membrane feed pressure, a similar differential pressure, and new permeate and brine compositions.
4. Steps 2 and 3 are repeated for each additional recirculation pass.
5. Total energy consumption is computed with the averaged membrane feed pressures and membrane differential pressures, the steady pump flow rates, and the pump and motor efficiencies. Permeate quality is computed by averaging the projection outputs.

Energy consumption figures for a range of overall recovery rates and fluxes are reported below.

Pump Efficiency Adjustments. CCD unit performance was slightly compromised by poor CP efficiency and leakage. Trial data shown in Figure 3 were adjusted based on a high-pressure pump and motor efficiency of 85 percent and a CP and motor efficiency of 60 percent—performance levels that can be achieved with commercially available pumps. An additional adjustment was introduced to eliminate the effect of CP leakage from the trial data. Resulting RO-specific energy consumption from Mediterranean

Figure 7. SWRO–CCD specific energy, modified test data vs. model, 4.1% feed salinity, 47% recovery, 85% HP efficiency, 60% CP efficiency

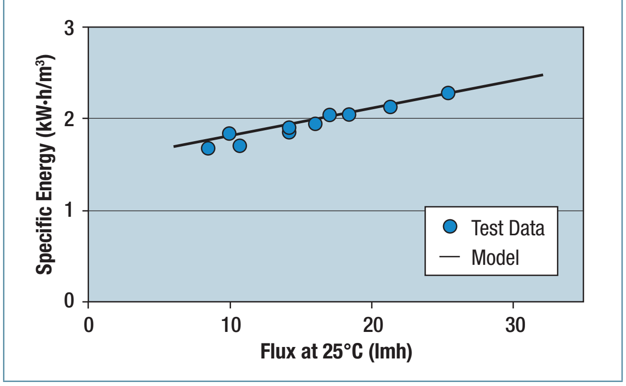
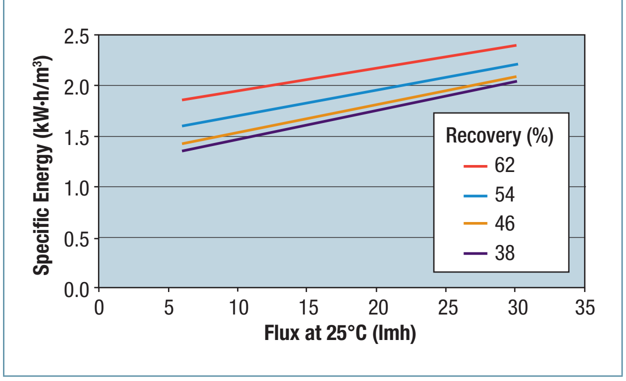


Figure 8. SWRO–CCD specific energy, modeling results, 3.5% feed salinity, SWC6 membranes, no fouling, 85% HP efficiency, 60% CP efficiency



Sea feedwater ranged from 1.6 kW·h/m^3 to 2.3 kW·h/m^3 as a function of normalized flux, as shown in Figure 7, which also shows a trend line from the pump and membrane performance model calculations described above. The excellent correlation between model and test data for specific energy consumption as a function of flux lends strength to field test results and modeling method.

Extrapolated Modeling Analysis. Having validated the membrane and pump energy model with test data, energy requirements for CCD in typical seawater of 3.5 percent salinity can be considered. Figure 8 provides model predictions of specific energy requirements for a CCD system using low-energy membranes operating at 38–62 percent recovery rates over a broad range of fluxes. These data indicate that seawater desalination with CCD technology at conventional flux and recovery rates can be accomplished with less than 1.5 kW·h/m^3 RO energy.

The validated performance model can be applied to the other trial conditions (Seacord et al, 2006). The process conditions corresponding to the lowest energy performance reported for that process were 9.5 lmh (6 gfd) flux and 35 percent recovery using low-energy membranes to desalinate California Pacific Ocean seawater with 31,688 ppm salinity at 15.2°C. The estimated RO specific energy consumption for a CCD process under these conditions is 1.34 kW·h/m^3.

Discussion

Operating Costs. Low-energy requirements of the CCD process presented in this article compare favorably with published values for SWRO systems operating in far less saline waters (Moch, 2007). Energy savings, together with reduced fouling and scaling provided by CCD technology, can result in significantly lower operating costs than are required for running conventional RO installations.

Capital Costs. The CCD process is a simple configuration of standard RO membranes and pumps. However, there are several major differences for equipment required for CCD and typical RO processes with isobaric ERDs. The CCD process

- does not require ERDs.
- uses a standard ERD CP operated at higher throughput and lower head.
- requires a slightly smaller high-pressure pump.
- requires a higher system volume.
- can be economically operated at higher flux with fewer membrane elements.

Regarding system volume, SCs can be shared by multiple CCD trains, thereby reducing a plant's total system footprint without adversely affecting operations or RO train independence.

Future Prospects. Having established that CCD operation is sound, the authors look ahead to possible practical applications. CCD technology is not confined to the flow, flux, recovery, and pressure conditions of the trials described in this article. It appears to be ideal for small, compact RO units, because any desired recovery is attainable even with a single-element module unit. Large-capacity units can be enabled with centrifugal high-pressure pumps with variable-frequency drive motors and use of shared SCs.

With elimination of ERD arrays, the number of moving components in large RO trains can be reduced significantly. Reduced membrane fouling—mechanical and biological—can be expected because of the wide variation in brine salinity. Therefore, less pretreatment will be necessary, and clean-in-place expenses will be reduced. Reduced fouling and cleaning could also extend membrane life. Desirable performance can be achieved over an extended flux range, reducing the number of membranes, associated footprint, and capital costs. The technology's flexibility allows for standard-sized units to be used for a broad range of feedwater conditions.

Conclusions

The CCD process configures standard RO membranes and pumps to substantially reduce primary energy consumption requirements of brackish and seawater desalination. Experience gained with SWRO-CCD and BWRO-CCD technologies reveals the following major benefits.

- Energy consumption is reduced.
- High overall recovery is attainable. Feedwater recovery is not limited by design. Each CCD unit can reach the ultimate possible recovery with a given water source, thereby minimizing source-water waste, reducing pretreatment costs, and reducing brine disposal expenses.
- Operation is flexible with regard to pressure, flow, recovery, and energy demand, even with a variable salinity source.
- Fouling and scaling should be reduced.
- Membrane performance should be excellent without exceeding membrane manufacturer's published specifications, even at high recovery and high flux.
- Installation costs should be reduced because common commercial components can be used, higher flux reduces the number of membranes required, ERDs are not required, and single-stage process designs are simple.

These combined assets make the CCD process a substantial breakthrough in low-cost desalination technology.

Desirable performance can be achieved over an extended flux range, reducing the number of membranes, associated footprint, and capital costs.

Acknowledgments

The authors acknowledge Via Maris Desalination for hosting and assisting with the demonstrations described in the article; Professor Avi Efraty for his development of the CCD process and much of the content on which this article is based; Ran Natanel Barak, Zviel Gal, and Joseph Septon for data collection and insights; and Mark Buser for insights and assistance with the article.

About the Authors

Richard L. Stover *(rick@desalitech.com), executive vice president, and* ***Nadav Efraty****, CEO, are with Desalitech–USA, Newton, Mass.*

Footnotes

[1]PX Pressure Exchanger, Energy Recovery, San Leandro, Calif.

[2]DWEER, Flowserve Calder, Irving, Texas

[3]Integrated Membrane Solution Design Software, Hydranautics, a Nitto Denko Company, Oceanside, Calif.

[4]Reverse Osmosis System Analysis, Dow Chemical, Midland, Mich.

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Editor's Note

This article is an updated, peer-reviewed version of a paper presented at IDA World Congress 2011, Sept. 4–9, Perth, Western Australia.