Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1168586

57 (2016) 26501–26506
November

Taylor & Francis
Taylor & Francis Group

High recovery, low fouling, and low energy reverse osmosis

Richard L. Stover

Desalitech Inc., Newton, MA, USA, email: rstover@desalitech.com

Received 8 October 2015; Accepted 2 March 2016

ABSTRACT

Desalination and water reuse using reverse osmosis (RO) are viable new water supply resources; however, traditional RO systems often create excess brine waste, do not fully utilize source water supplies, and consume too much energy. Newly emerging closed-circuit RO processes improve RO performance and reduce its cost by increasing recovery, reducing fouling and scaling, and reducing energy consumption. This performance has been documented in dozens of RO installations in a range of applications. In particular, a closed-circuit RO unit operated on groundwater with a silica concentration of 59 ppm at recovery rates of up to 93.5%, producing brine silica concentrations exceeding 900 ppm. This recovery rate was sustained at neutral pH, with modest anti-scalant dosing and no scaling-related CIP requirements. A traditional RO system operating in feedwater with this concentration of silica would be limited to 76% recovery or less, corresponding to more than 3 times the production rate of brine concentrate. At another site, seawater with a total dissolved solids content of 35,329 ppm was desalinated with 5.5 kWh/1,000 gal (1.45 kWh/m^3) of RO pump energy. This represents the lowest energy consumption ever reported for seawater RO at a comparable recovery rate and flux.

Keywords: Reverse osmosis; Closed-circuit; CCD; High recovery

1. Introduction

Freshwater scarcity is one of the most serious global challenges of our time. In the US and other developed countries, industry is responsible for nearly 60% of freshwater withdrawals from the environment. Industry and agriculture together are responsible for about 90% of withdrawals globally [1]. This puts tremendous pressure on water resources which will only increase with growth. Desalination and water reuse are viable new water supply resources. Among the methods available for removing dissolved species such as salts and trace contaminants and thereby purifying water and wastewater, reverse osmosis (RO) has widely demonstrated superior reliability and cost-effectiveness. For these reasons, RO is one of the fastest growing water treatment technologies [2].

First commercialized in the 1970s, RO is widely applied today. However, traditional RO systems often create excess brine waste, do not fully utilize source water supplies, and consume too much energy. This waste increases when using RO to treat problematic water, such as feed water with varying levels of salinity or bio-activity. Although incremental performance improvements have been made, such as advancements in membrane technology, pretreatments, and chemical

Presented at the IDA 2015 World Congress (Desaltech 2015) 29 August–4 September, 2015 San Diego, CA, USA

additives, RO systems have not changed much over the decades.

For most industrial RO applications, raising recovery, thereby reducing waste brine generation, represents the greatest cost-saving opportunity. For brine concentration and seawater RO, reducing energy consumption has the greatest prospect for lowering overall costs [3]. Closed-circuit or semi-batch RO is an emerging process that promises to improve these and many other aspects of RO performance [4–7]. This paper describes the closed-circuit RO process and how it can be used to improve RO performance.

2. Process description

Closed-circuit RO systems are built with standard RO components in a new process configuration as illustrated in Fig. 1. Pressurized feedwater and recirculated brine concentrate are fed to the membrane array without releasing concentrate from the process until a desired recovery level is reached; then, the brine is throttled out of the process, displaced from the system with fresh feed from the high-pressure pump in a single plug flow sweep. The process then returns to closed-circuit operation, during which there is no brine reject stream. Permeate is produced at a rate equal to the flow rate of the high-pressure pump during closed-circuit operation and at a reduced rate during the plug flow flush. The resulting recovery rate is the total amount of permeate produced divided by the amount of water fed to the system. Recovery rates of over 97% with a single stage of membrane elements have been demonstrated [6].

For relatively low-recovery, high-pressure applications, such as brine concentration or seawater desalination, an alternative closed-circuit RO process is used to maximize energy savings. This version of the closed-circuit RO process displaces spent brine with pressurized feedwater from a side conduit. The exchange, emptying, and refilling of the side chamber are done under hydrostatic conditions with almost no loss of pressure energy. The process is illustrated in Fig. 2 [4,8].

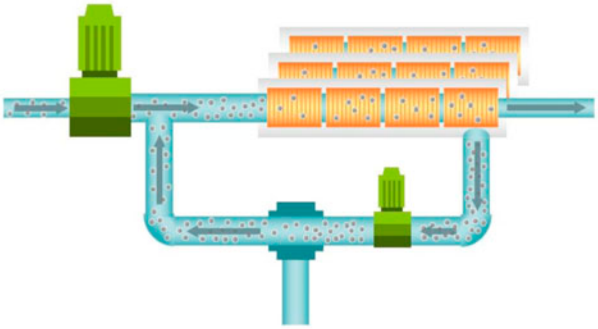

Fig. 1. Closed-circuit RO process schematic diagram.

3. Design and modeling

The performance of CCD-RO systems can be predicted using standard membrane projection programs in the same way they do for conventional RO systems. Multiple iterations of these models provide estimates of the pressure requirements and permeate quality output of CCD-RO systems. These models can also be used to study the performance of individual membrane elements in multi-element arrays. Multiple flows, recoveries, and membrane configurations can be examined in the model to test the flexibility of alternative systems and operating conditions. The warnings generated by the projection programs identify operating limits. Specifically, this experimental modeling approach can give an indication of when lead membrane element flux is high, thereby predicting when these elements are at greatest risk of fouling. It can indicate when cross-flow is low, thereby identifying excess concentration polarization and the associated risk of fouling and scaling. It can also allow consideration of how feed composition, temperature changes, and membrane age affect system performance. Such studies are well-documented in referenced papers [7–9].

Design results for a typical example system were developed and documented in an appendix to this paper.

3.1. Give design and modeling example

The benefits provided by CCD-RO systems anticipated by modeling analysis are borne out in field installations as described below.

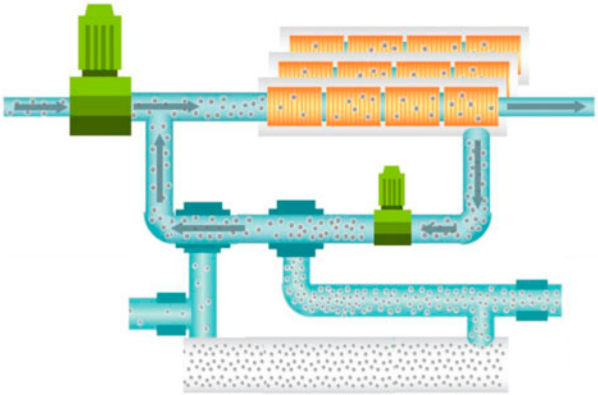

Fig. 2. Closed-circuit RO process with side conduit.

4. Results

CCD systems are at work in a range of applications from sea and brackish water desalination to wastewater reuse and ultrapure water production. The following are selected examples of these installations and their key performance characteristics.

4.1. Higher recovery

High recovery operation conserves source water and minimizes brine disposal. In addition, high recovery operation can reduce feedwater pretreatment requirements and the associated costs. These are highly desired performance aspects in most industrial and brackish water purification applications [3].

Closed-circuit RO processes allow direct control of recovery. Brine is recirculated as the system operates at 100% recovery until it is released from the system. Therefore, the recovery rate is an operator-controlled set point. Closed-circuit RO systems have achieved over 97% recovery with a single stage of membrane elements, whereas traditional brackish RO requires multi-staging to achieve recovery rates greater than about 50%.

As the concentration of salts in a semi-batch recirculation loop increases, solubility levels can exceed saturation. However, precipitation typically does not begin instantaneously. Time is required for crystal seeding and growth. The time required for precipitation to occur once saturation is exceeded is known as induction time [9]. If a closed-circuit RO process is operated at a recovery rate that results in supersaturation of one or more water constituent, the amount of time that supersaturation exists is typically shorter than the induction time for precipitation. At the end of each sequence, the brine concentrate is fully flushed from the system. This stops and can even reverse the precipitation mechanism. In contrast, the water composition at any given position in the membrane array of a traditional RO system is relatively constant, with the highest concentration levels occurring closest to the membrane surface and near the end of the membrane array. If the concentration of any constituent exceeds saturation in a traditional RO system, precipitation will likely occur resulting in membrane scaling.

Studies have shown that recovery rates that produce high degrees of supersaturation of sparingly soluble salts can be sustained in batch RO processes, with or without the use of scale inhibitors. Scale depositions, particularly those of silica and calcium sulfate, can be mitigated by batch cycling, allowing maintenance of membrane permeability without chemical cleaning [10]. These results are directly applicable to batch-like closed-circuit RO processes in which intrinsic system volumes are typically much smaller and supersaturation durations can be much shorter than induction times for scale precipitation. The inherent resistance to scaling offered by closed-circuit RO processes make sustained operation at high recovery rates and/or with reduced chemical use possible, even with source waters with high levels of sparingly soluble salts.

A closed-circuit RO unit operates in Southern California at an agricultural site where the silica concentration in the groundwater is 59 ppm. Recovery rates of up to 93.5% have been sustained, corresponding with brine silica concentrations exceeding 900 ppm at neutral pH, with modest anti-scalant dosing and no scaling-related CIP requirements. A traditional RO system operating in feedwater with this concentration of silica would likely be limited to 76% recovery, corresponding to more than 3 times the production rate of brine concentrate.

4.2. Better fouling resistance

Water reuse and recycling represent a significant opportunity for new water supply. Most wastewaters can be purified to drinking water quality with treatment schemes that include RO, but there are also many non-potable uses for recycled water. One of the challenges for RO operation in wastewater is membrane fouling. This problem is especially acute in municipal wastewater recycling where RO feedwaters can contain significant biological material and activity.

Two means of limiting fouling in RO systems are reducing and controlling flux and maximizing cross-flow [11]. Closed-circuit RO membrane arrays typically consist of three or four elements, numbers which have been found to optimally balance performance and costs. These are shorter than the arrays in most traditional RO systems in which six to eight membrane elements in series are used to maximize recovery per stage and thereby reduce the number of stages required to achieve a target overall recovery rate. Short membrane arrays inherently provide more balanced flux distribution along the array. In particular, the flux through the first or head element in each membrane housing in a short membrane array is less than that in a long membrane array with the same average flux [12]. This helps reduce head element fouling.

Closed-circuit RO systems include a circulation pump dedicated to providing cross-flow. Cross-flow washes membrane surfaces and reduces the effects of both fouling and scaling. In closed-circuit RO systems, the circulation pump can be adjusted to change cross-flow without altering flux or system recovery. Cross-flow can also be changed in traditional RO systems by opening or throttling the concentrate valve; however, this also changes flux and cross-flow. The ability to independently control cross-flow is unique to RO systems with recirculation. This flexibility allows the plant operator to easily adjust system operations in response to feedwater composition or temperature, membrane age or degree of fouling, or operational requirement changes. However, for most changes, a closed-circuit RO system responds automatically, changing recovery as needed to meet a maximum pressure or conductivity set point, and this contributes to the reliability of the process.

As the salinity throughout the closed-circuit RO process cycle rises and falls over the course of a closed-circuit sequence, the osmotic pressure changes. This changes the movement of water across biological cell membranes, producing osmotic stress, and in some cases, a sudden change in the solute concentration around a cell, causing a rapid change in the movement of water across its cell membrane. Such an osmotic shock can disrupt biological fouling including biofilm formation [13].

Effective use of a closed-circuit RO system for water reuse was recently demonstrated by tests at a Los Angeles County Sanitation facility in Whittier, California. High recovery operation is important to the Sanitation Districts of Los Angeles County because most of the county's treatment facilities are located inland where concentrate disposal can be expensive and cumbersome. A closed-circuit RO system was operated at 93% recovery with fluxes of 9–13 gallons per square foot per day (gfd, 15–22 liters per square meter per hour, (lmh)) for several months on tertiary effluent with a conductivity of 1,000 uS/cm. Clean in place (CIP) was required approximately every 6 weeks to restore membrane performance—a frequency that was considered normal and acceptable for an RO system operating at 75% recovery. In other words, the closed-circuit RO process was able to operate without extra CIP requirements while producing less than 1/3 the amount of concentrated reject as would be produced by a typical traditional RO system [14].

The Singapore Public Utilities Board (PUB) recycles wastewater for direct use in industrial applications and for indirect use for potable water supply. Secondary effluent is treated with microfiltration, RO, and ultraviolet disinfection to create NEWater. The current NEWater process recovery efficiency, based on 2-stage RO, is 75%. Since NEWater is expected to meet 55% of Singapore's water demand by 2060, there is a need to increase NEWater recovery efficiency. Closed-circuit RO is under investigation at the Kranji NEWater factory as a means to achieve this need. The closed-circuit RO system there has operated at 88% recovery with a CIP frequency comparable to that of the 75% recovery system [15].

4.3. Lower energy consumption

The high-pressure pump or pumps account for the majority of the energy consumed by an RO process. Enough pressure must be applied to overcome the osmotic pressure barrier that exists because of the ionic strength of the water being desalinated plus any resistance to flow through the membrane. Generally, higher feedwater salinity, higher flux, and higher recovery result in higher feed pressure requirements and higher energy consumption [16]. Reducing energy consumption is critically important for seawater desalination. Up to 75% of the cost of ownership of a seawater RO operation is the energy required to drive the high-pressure pumps [3].

Closed-circuit RO systems lower energy consumption by lowering the average feed pressure compared to that required by most traditional RO processes operating at the same feed salinity, flux, and recovery. The feed pressure at the beginning of each closed-circuit semi-batch sequence corresponds to the osmotic pressure of the feedwater. As the concentration of salts in the recirculation loop increases, the pressure required to maintain permeate flow increases. The maximum feed pressure corresponds to the osmotic pressure of the final brine. The average of the initial and final feed pressures dictates the average duty of the high-pressure pump and its energy consumption [6–8]. This average pressure is lower than the constant feed pressure required to drive a single-stage traditional RO system. Traditional RO feed pressure corresponds to the osmotic pressure of the final brine. Multiple-stage systems can be used to lower the average feed pressure to closer to the osmotic pressure if inter-stage boosting is applied [16].

These concepts are illustrated in Fig. 2 below where applied feed pressure and the osmotic pressure requirement are plotted as a function of percent recovery in arbitrary units. The feed pressure in a single-stage traditional RO system must be sufficient to force permeate through the tail membrane elements where the osmotic pressure barrier is highest in the array; however, this pressure is excessive for the lead elements. The gap between the applied feed pressure and the osmotic pressure barrier is reduced with multiple staging with multiple pumps, reducing energy consumption. The closed-circuit RO feed pressure, labeled as CCD-RO in Fig. 3, "hugs" the osmotic pressure curve, providing the energy-saving benefits of

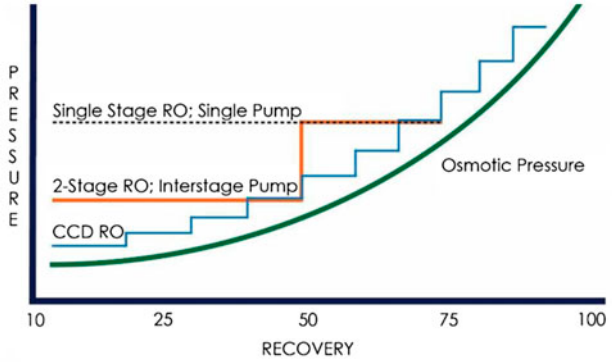

Fig. 3. Applied feed pressure and osmotic pressure vs. recovery.

traditional RO systems with many stages and pumps without requiring many stages or pumps. The energy savings benefit of a closed-circuit RO system corresponds with the area between the curves.

One way that energy consumption is reduced in traditional RO systems is using energy recovery devices to return energy from the brine to the membrane feed [17]. In a high-pressure single-stage RO systems, an isobaric energy recovery device can recover more than 90% of the brine energy. In multi-stage RO systems, isobaric devices are not used because the pressure of the concentrate from the final stage is generally much higher than the feed pressure of the first stage. Therefore, if energy recovery devices are used in multi-stage systems, lower-efficiency turbine-type devices are required. Closed-circuit RO systems significantly reduce brine pressure prior to releasing it from the process thereby conserving this energy and eliminating the need for energy recovery devices.

A 44 gallon per minute (250 m^3/d) closed-circuit RO unit for seawater RO was operated in Mediterranean seawater with an average salinity of 4.1% and a temperature in the range of 72–90 F (22–32˚C). A photograph of the system is given in Fig. 4. A range of recovery rates from 40 to 53% and fluxes from 5 to 15 gfd (8–26 lmh) were tested. Specific energy consumption by the high-pressure pump and circulation pump was measured in the range of 6.4–9.8 kWh/1,000 gal (1.7–2.6 kWh/m^3). The corresponding specific energy consumption normalized to 45% recovery operation at 7.5 gfd (14.3 lmh) flux from standard seawater of 35,000 ppm total dissolved solids (TDS) is 6.1 kWh/1,000 gal (1.6 kWh/m^3). This very low energy consumption rate compares very favorably with the energy consumption rates of state-of-the-art SWRO systems which typically range from 8 to 11 kWh/1,000 gal (2–3 kWh/m^3) [7,8].

Fig. 4. Closed-circuit seawater RO system.

Another study of seawater desalination with closed-circuit RO was conducted with a similar size system equipped with Nano H_2O Quantum Flux membranes and a Danfoss APP high-pressure pump. The energy consumption of the high-pressure and circulation pumps was measured at 47% recovery and 9.2 lmh flux, as the system produced 518 ppm permeate from 35,329 ppm TDS feedwater. After correction of the temperature from 61 to 77 F (16–25˚C), the specific energy consumed was 5.5 kWh/1,000 gal (1.45 kWh/m^3) and the permeate TDS 682 ppm [18]. This represents the lowest energy consumption ever reported for seawater RO at a comparable recovery rate and flux.

The same system was tested by MWH Global in a project that was partially funded by the Water Reuse Research Foundation. This study compared the performance of a closed-circuit RO process to that of a traditional seawater RO process equipped with isobaric energy recovery devices. Over the range of flux and recovery rates tested, the closed-circuit system consumed 16–25% less energy while producing similar permeate quality [19].

5. Conclusions

Desalination and water reuse with RO processes can help address global water scarcity by providing new water resources. Newly emerging closed-circuit RO processes improve RO performance and reduce its cost by increasing recovery, reducing fouling and scaling, and reducing energy consumption. This performance has been documented in RO installations in a range of applications.

References

[1] UNESCO, Water for People, Water for Life, United Nations World Water Development Report, United Nations Educational, Scientific and Cultural Organization, 2003.

[2] C. Gasson (Ed.), Global Water Intelligence, Industrial Desalination and Water Reuse, August 2012.

[3] R. Stover, A primer on reverse osmosis technology, Chem. Eng. 121 (2014) 39–44.

[4] A. Efraty, Apparatus for continuous closed circuit desalination under variable pressure with a single container, US Patent No 7,628,921, 2010.

[5] A. Efraty, Continuous closed-circuit desalination apparatus without containers, US Patent No 7,695,614, 2010.

[6] A. Efraty, Closed circuit desalination series no-4: High recovery low energy desalination of brackish water by a new single stage method without any loss of brine energy, Desalin. Water Treat. 42 (2012) 262–268.

[7] A. Efraty, R. Barak, Z. Gal, Closed circuit desalination—A new low energy high recovery technology without energy recovery, Desalin. Water Treat. 31 (2011) 95–101.

[8] R. Stover, N. Efraty, Low-energy consumption with closed-circuit desalination, IDA J. 4(3) (2012) 12–19.

[9] V.A. Shneidman, M.C. Weinberg, Scaling properties of induction times in heterogeneous nucleation, J. Chem. Phys. 95 (1991) 9148.

[10] A. Tarquin, G. Delgado, Concentrate enhanced recovery reverse osmosis: A new process for RO concentrate and brackish water treatment, in: Proceedings of the American Institute of Chemical Engineers Meeting, Pittsburg, PA, paper number 272277, October 2012.

[11] C. Bartels, R. Boda, A. Abrar, Wastewater reuse RO plant: Road from troubled to stable operation, in: Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China, October 2013.

[12] R. Stover, Permeate recovery and flux maximization in semi-batch reverse osmosis, in: Proceedings of the AMTA/AWWA Membrane Technology Conference and Exposition, San Antonio, TX, February 2013.

[13] E. Drioli, L. Giorno (Eds.), Comprehensive Membrane Science and Engineering, vol. 1, Google eBook, 2010.

[14] B. Mansell, T. Nikonova, P. Ackman, B. Langpap, C. Tang, R. Tremblay, P. Friess, Evaluation of RO concentrate treatment and disposal options for the Santa Clarita valley, in: Proceedings of the 29th Annual WateReuse Symposium, Dallas, TX, September 2014.

[15] H. Wang, X.Q. King, K. Lee, J. Chen, H. Seah, Pilot study of closed circuit desalination technology to increase NEWater recovery, in: Proceedings of the Singapore International Water Week, Singapore, July 2014.

[16] M. Elimelech, W.A. Phillip, The Future of seawater desalination: Energy, technology, and the environment, Science 333 (2011) 712–717.

[17] R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices, Desalination 203 (2007) 168–175.

[18] A. Efraty, Z. Gal, Closed circuit desalination series No-18: Record low energy in closed circuit desalination of Ocean seawater with NanoH$_2$O elements without ERD, Desalin. Water Treat. 57(20) (2016).

[19] A. Subramani, J.G. Jacangelo, N. Voutchkov, Desalination energy minimization using nanocomposite and semi-batch RO, in: Proceedings of the 18th Annual Water Reuse and Desalination Research Conference, Las Vegas, NV, May 2014.