Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1126412

57 (2016) 20228–20236
September

Taylor & Francis
Taylor & Francis Group

CCD series no-21: illustration of high recovery (93.8%) of a silica containing (57 ppm) source by a powerful technology of volume reduction prospects

V. Sonera, J. Septon, Avi Efraty*

Desalitech Ltd, P.O. Box 132, Har Adar 90836, Israel, email: avi@desalitech.com (A. Efraty)

Received 24 April 2015; Accepted 10 October 2015

ABSTRACT

The Fabbri farm well-water source (TDS: 1,304 ppm; SiO_2: 57 ppm) in the California Central Valley was desalinated with up to 93.8% recovery under extreme silica supersaturation (930 ppm) conditions using a closed-circuit desalination (CCD) pilot with a single module (8´´) of three elements at pH 5.5 in the presence of an antiscalant (FLOCON-260). Experimental trials of the Fabbri source at 17.2 and at 19.6 lmh 7.2 are described in this study with complete online data provided for an extended 8-h trial at 17.2 lmh of 92.8% recovery with consecutive sequential pressure variation of 6–14 bar and electric conductivity (EC) of average permeates (230 μS/cm) and of brine (23,450 μS/cm) cited in parentheses and specific energy consumption of 0.918 kWh/m^3 with high-pressure pump efficiency of 55%. Analysis of the consecutive sequential online data during the extended and all other trials revealed unchanged module pressure difference and minor variations of maximum and minimum applied pressures, EC of permeates and recycled concentrates, and a sequential period which ruled out any scaling and/or fouling effects. The findings of this study clearly suggest the viability of the CCD as a powerful technology of considerable prospects for volume reduction applications on route to zero liquid discharge.

Keywords: RO; Closed-circuit desalination (CCD); High recovery; Low energy; Silica removal; Silica supersaturation; Volume reduction

1. Introduction

Silica (SiO_2) is a compound comprised of the two most abundant elements on earth. It is commonly found in nature as quartz (sand), various silicate minerals, as well as in various living organisms. Silica in its different form is used for wide range applications [1] including those related to structural materials (e.g. cement and glass), microelectronics, components used in the food industry, and others. Silica is found in ground and surface water in various concentrations up to ~120 ppm, the solubility limit under pH 6–8, and temperature of 25˚C [2]. The limited solubility of silica and its ability to create insoluble silicates with certain metal ions pose serious problems to many industrial water systems and the need to cope with prevention and/or cleaning of silica-based deposits [3]. Reverse osmosis systems are particularly affected by silica scaling since they are required to operate at lower recovery in order to prevent irreversible damage to membranes created by silica scaling. Many of the worldwide water sources contain relatively high amounts of silica which confine their RO desalination even in the presence of efficient antiscalants and this

*Corresponding author.

1944-3994/1944-3986

translates to waste of water and increased energy consumption in such operations. Since the availability of water supplies has declined significantly in many parts of the world due to climate changes with enhanced depletion/deterioration of ground/surface water sources, this led to the need for new high recovery cost-effective RO techniques in order to save on freshwater and/or reduce the volume of brine received during the RO desalination of brackish water (BWRO).

Conventional RO system designs [4] are based on the plug flow desalination (PFD) approach with increased recovery concomitant with a longer line of tail-to-head connected elements. Common BWRO PFD designs normally comprise of two-stage or three-stage module configurations, each of six elements, which are operated with fixed applied pressure of feed and allow nominal recovery of 75 and 87%, respectively. Worldwide experience gained with conventional BWRO PFD plants revealed that such systems show high propensity to silica scaling even in the presence of effective antiscalants and this is most probably due to their design and mode of operation. In this context, noteworthy in particular is the newly emerging versatile closed-circuit desalination (BWRO-CCD) technology [5] of high recovery irrespective of the number of elements per module and low energy consumption without need for energy recovery means from brine, which was exemplified in recent years for numerous applications such as upgrade of domestic supplies with 96% recovery [6], nitrate removal from drinking water [7], desalination of clear domestic effluents [8,9], and desalination of brackish water [10–12]. This study illustrates the application of the CCD technology for high recovery (93.8%) and low energy (0.65 kWh/m^3) desalination of a feed source (TDS: 1,304 ppm) with 37 ppm silica.

2. Fabbri BWRO-CCD pilot deign and operational modes

The schematic design of the Fabbri BWRO-CCD ME3 (E = ESPA2-MAX) pilot displayed in Fig. 1 comprises a single module (8´´) with three ESPA2-MAX [13] elements and a spacer in front with other principle components specified in the figure. Pressurized line and valves in the pilot are of 300 psi rating and made of SS316. The Fabbri unit is one of four fully equipped identical pilots intended for the performance evaluation of difficult water sources prior to the design of a full-scale CCD plants.

The pilot under review is programmed to perform a two-step consecutive sequential desalination process with CCD experienced most of the time (>90%) and brief PFD steps initiated between CCD sequences for brine replacement by fresh feed after the designated maximum applied pressure of desired recovery is reached. The CCD cycles in the process are carried out under fixed flow and variable pressure conditions with same flow rates of pressurized feed and permeate ($Q_{hp} = Q_p$) and fixed module recovery (MR) expressed by $Q_p/(Q_p + Q_{cp}) = Q_{hp}/(Q_{hp} + Q_{cp})$ of 100% instantaneous recovery since $Q_p/Q_{hp} = 1.0$, whereas the PFD steps proceed with a brine rejection flow (Q_b) according to the flow balance equation $Q_{hp} = Q_p + Q_b$, or $Q_{hp} = Q_p + Q_{cp}$, with low recovery expressed by $Q_p/(Q_p + Q_b)$, or $Q_p/(Q_p + Q_{cp})$ since at this step $Q_b = Q_{cp}$. Set points (SPs) of operations whereby the pilot is being controlled include the constant flow rates of HP under CCD ($SP_{hp\text{-}CCD}$) and under PFD ($SP_{hp\text{-}PFD}$) conditions, the fixed-flow rate of CP (SP_{cp}) during CCD, and the maximum applied pressure ($SP_{p\text{-}max}$) during CCD. The operational SPs in this system provide an infinite number of combinations, which may be changed online, with enormous performance flexibility and versatility with choice of flow rates also dictates both MR and cross-flow irrespective of selected recovery. The only manual control in the system is that of minimum pressure experienced during PFD achieved by the manually selected partial opening setup of the MV. It should be pointed out that electric conductivity (EC) measurements of recycled concentrates, especially at maximum applied pressure, were done by sampling and this in order to avoid silica deposition on the probe as well as to enable visual inspection of the measured solution for clarity.

3. Fabbri BWRO-CCD pilot—experimental trials procedures

Fabbri's well-water supplies comprise according to analytical data of the following average constituents (ppm): Ca, 280: Mg, 5.0: Na, 110: NH_4, 0.17: Sr, 1.2: HCO_3, 150: Cl, 280: SO_4, 380: NO_3, 40: SiO_2, 57: CO_3, 0.98: CO_2, 2.65: TOC, 1.45: TDS: 1,304; pH 7.9; and EC, 1,840 μS/cm. Considerable amounts of particulate matter are found in this water source and this required an extensive pretreatment by means of multimedia including an active-carbon column to remove the organic residues before supplies admitted to the pilot through a micronic filter (1.0 μ). All the trials with the Fabbri pilot were carried out at pH ≈ 5.5 with antiscalant (FLOCON-260) dosing (4.5–5.0 mg/l) at CCD flux (lmh) of 17.2 (MR = 26%) and 19.6 (MR = 29%). The $SP_{hp\text{-}CCD}$ and SP_{cp} set points of operation during the trials manifested the specified flux and MR conditions, and the PFD brine flush-out steps

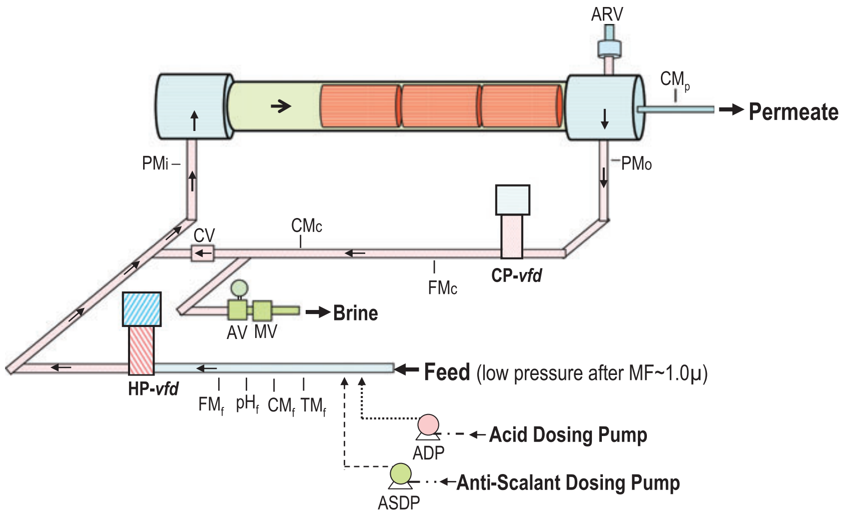

Fig. 1. Schematic design of the CCD pilot use for the desalination of the Fabbri water source. Abbreviations: HP-*vfd*, high-pressure pump; CP-*vdf*, circulation pump; ADP, acid dosing pump; ASDP, antiscalant dosing pump, AV, actuated valve; MV, manual valve; CV, check valve; ARV, air release valve; FM, flow meter; pH, pH monitor; CM, EC monitor; TM, temperature monitor; PM, module pressure monitor; MF, micronic filter. Subscripts: f, feed; c, recycled concentrate; i, inlet; and o, outlet.

were carried with an accelerated flow rate of HP (~4.1 m^3/h) irrespective of the selected flux conditions. Maximum CCD applied pressure set point ($SP_{p\text{-max}}$) of different trials was raised systematically in the range of 10.3(150)–16.9 bar (245 psi) with increased maximum applied pressure manifesting increased recovery. Special attention during the trials of increased recovery was given to the monitoring of parameters which signify fouling and/or scaling such as module pressure difference (Δp), EC of permeates, and EC and clarity of brine samples retrieved at the end of sequences. Under the CCD fixed flow and variable pressure conditions, scaling is manifested by increased Δp, and the creation of thin colloidal silica film/layer on membrane surfaces causes fouling detected immediately by increased minimum CCD applied pressure and by increased salt rejection manifested by lower EC of permeates. Inspection of the retrieved brine samples for clarity provided another indication of scaling and/or the presence of colloidal silica in the closed circuit and their EC together with that of the feed-enabled sequence recovery estimates of trials.

A daily routine experimental procedure of 9–10 h covered 1–3 trials of same flux and MR at different maximum applied pressure set points ($SP_{p\text{-max}}$), if more than one trial was conducted. At the conclusion of each day, the pilot was stopped, remains in the system were flushed out with permeates, multimedia refreshed, and micronic filter inspected for clearance. At start of each day, the correct flow rates, including those of the acid and antiscalant dosing systems, were confirmed before data collection resumed. In order to get reproducible trials results, the experimental protocol had to be followed up rather strictly, since even minor malfunction could have created irreversible damage to membranes under the high supersaturation concentration of silica encountered during the course of the referred trials. The main focus of this study was on trials over 90% recovery, since preliminary experiments below this recovery level never revealed any signs of neither scaling nor fouling due to silica.

4. Fabbri BWRO-CCD pilot—experimental results

4.1. *Results of the long 26/08/2014 trial at 17.2 lmh and maximum pressure of 14.1 bar*

Online results of an eight-hour trial on 26/08/2014 (11:00–19:00) with Fabbri feed (1,870 μS/cm) at 17.2 lmh flux and maximum applied pressure set point of 14.1 bar (205 psi) are displayed in Figs. 2a–2g2 with cited in parentheses metered volumes of feed (20.76 m^3) and permeate (19.27 m^3) and energy consumption of HP + CP (17.68 kWh) according to which the overall recovery of this trial was 92.8% with specific energy of 0.918 kWh/m^3. A recycled concentrate sample of 20,600 μS/cm was analyzed for TDS by a professional laboratory and the established result of 15,000 ppm corresponds to μS/cm/TDS ratio of 1.373; whereby, EC of brine could be converted to concentration and compared with that of feed (μS/cm/TDS = 1.411). The only EC experimental data for

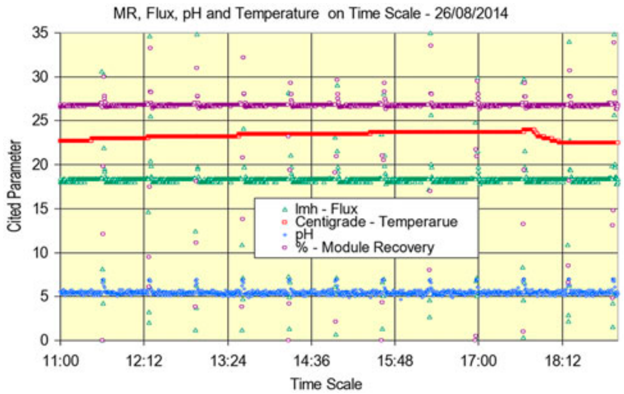

Fig. 2a. Monitored flux, MR, pH, and temperature on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

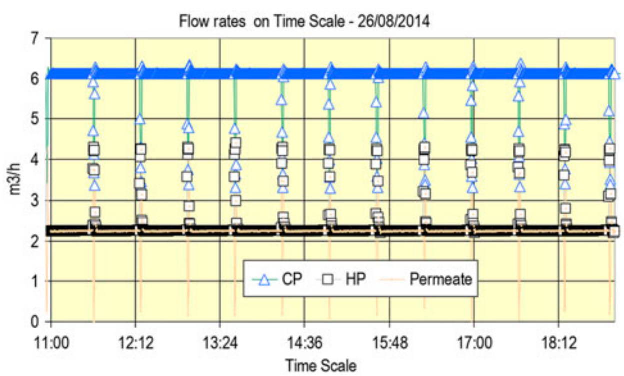

Fig. 2b. Monitored flow rates on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

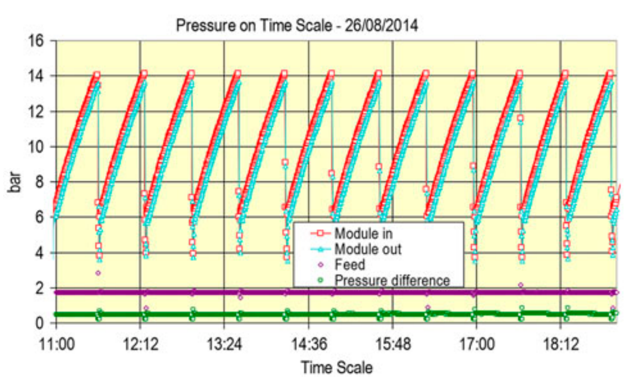

Fig. 2c. Monitored pressure data on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

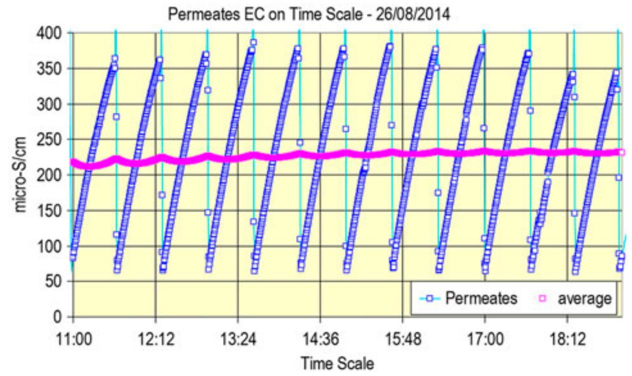

Fig. 2d. Monitored EC data of permeate on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

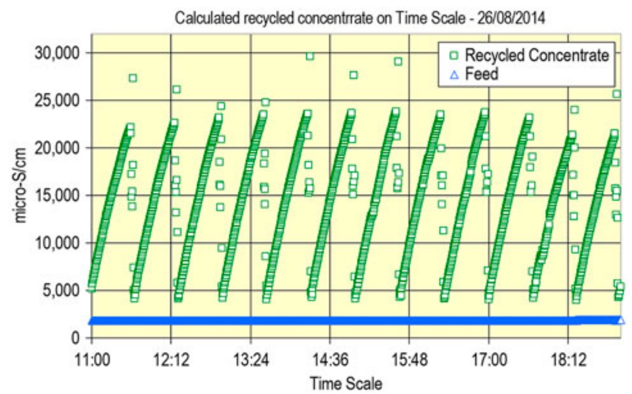

Fig. 2e. Monitored EC data of feed (average 1,870 µS/cm) and calculated EC of recycled concentrates from that of permeates on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

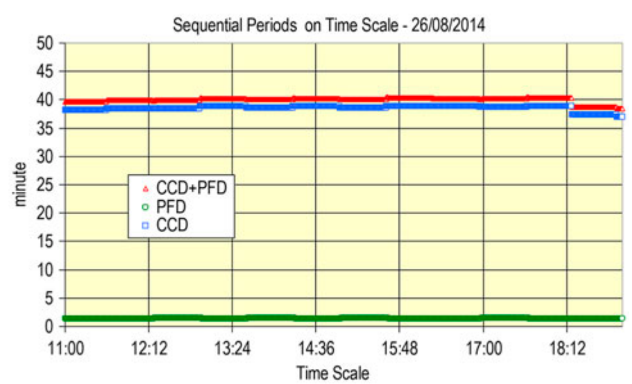

Fig. 2f. Monitored CCD, PFD, and CCD + PFD sequential periods on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

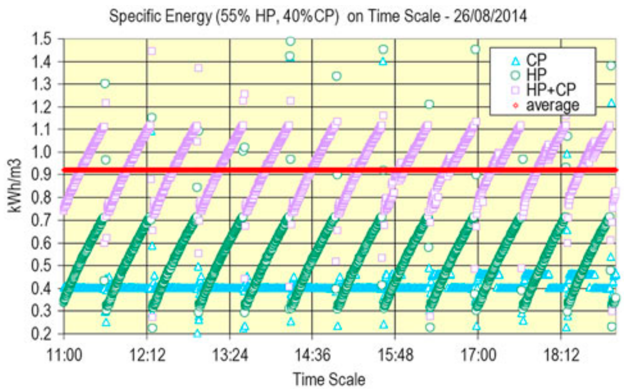

Fig. 2g1. Calculated specific energy on the basis of flow rates, pressures, and efficiencies of pumps with average equivalent to the experimental result (0.916 kWh/m^3) on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

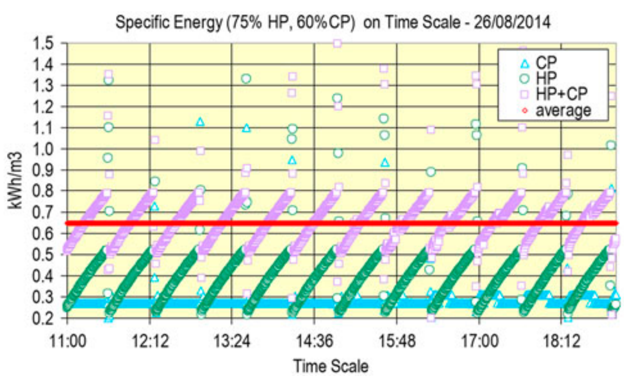

Fig. 2g2. Calculated specific energy on the basis of flow rates, pressures, and improved efficiencies of pumps with a projected average of 0.65 kWh/m^3 on a timescale over an 8-h period during the 17.2 lmh flux trial on 26 August 2014.

recycled concentrates in the trial under review is that for rejected brine (23,450 μS/cm) which corresponds to 16,619 ppm.

All the online monitored data over the eight-hour trial on 26 August 2015 revealed a consistent consecutive sequential pattern with long CCD cycles experienced most of the time and brief PFD brine flush steps according to the predetermined set points of operations. The control set points of constant flow rates, flux, MR, and pH during the CCD cycles are fully realized in the monitored data revealed in Figs. 2a and 2b, and the former also shows a small range of temperature variability. The fixed-flow variable pressure CCD characteristic features in this trial are manifested by the online pressure data in Fig. 2c. Noteworthy in particular in reference to CCD pressures (Fig. 2c) are the near constant module pressure difference (Δp = 0.52 ± 0.03 bar), repeated minimum applied pressure of 6.0 bar, and set point ($SP_{p\text{-}max}$) defined maximum applied 14.0 bar which rule out entirely the possibility of any fouling and/or scaling in the trial under review of 92.8% recovery based on monitored volumetric data. The CCD permeates' EC pattern displayed in Fig. 2d shows small changes of maximum and minimum sequential values consistent with the small temperature variations revealed in Fig. 2a, since lower temperature expected to affect lower EC and vice versa. Creation of a thin colloidal silica film on the surface of the membranes in this trial can be ruled out since should have resulted by a noticeable sharp decline of maximum and average EC of permeates.

Online data of EC of cycled concentrate were not available since such data were taken manually mainly for recycled concentrate (brine) at maximum applied pressure after inspection for clarity of the retrieved samples. The knowledge of flux, temperature, and salt diffusion coefficient does allow calculation of EC for recycled concentrates from that of permeates and such calculated results for the trial under review are displayed in Fig. 2e together with a reference to the average experimental feed EC (1,870 μS/cm) during this trial. According to EC data of feed and brine (23,450 μS/cm), the estimated recovery of this trial is 92.02%. If EC data are converted to ppm using the previously cited factors (1.411 for feed and 1.373 for brine), the estimated recovery on the basis of ppm is 92.26%. The aforementioned recovery estimates are consistent with the volumetrically established recovery of 92.8% and the small differences most probably reflect the precision of data collection and the accuracy of the EC/ppm ratio estimation of recycled concentrates. Moreover, the consistency of recovery determined by different techniques also suggests that the calculated projections of the consecutive sequential EC variations of recycled concentrates displayed in Fig. 2e are essentially correct.

In consecutive sequential CCD processes under fixed flow and variable pressure conditions, a basic parameter feature pattern is repeated on the timescale and changes in the pattern may arise from variations of feed salinity and/or temperature and/or due to fouling and/or scaling factors and/or malfunctions of controlled pumps. Online data displayed in Figs. 2a–2e reveal a highly consistent pattern on the timescale including with respect to the uniformed sequential periods of ~40 min displayed in Fig. 2f with CCD (~38 min/sequence) experienced ~95% of the time and PFD (~2.0 min/sequence) ~5% of the time. The highly consistent sequential pattern on the timescale in the trial under review implies small feed salinity and/or temperature variations as was indeed monitored as well as a process clear of fouling and/or scaling factors. Formation of a thin colloidal silica film on the surface of membranes in this trial of 6–14 bar applied pressure variations (Fig. 2c) should have created a noticeable sharp increase in the minimum applied pressure with a declined CCD sequence duration, since the maximum applied pressure is controlled by a fixed set point. In simple terms, the consistently repeated sequential CCD and PFD periods revealed in Fig. 2f, also rule out entirely the possibilities of scaling and/or fouling effects during the course of this trial.

Specific energy consumption during the course of the trial under review (0.918 kWh/m^3) which was determined from the cumulative monitored volume of permeates and energy during the entire trial could also be assessed from online flow and pressure parameters of HP (55% efficiency) and CP (40% efficiency) and the sequential variations of specific energy encountered according to this approach are displayed in Fig. 2g1. The Fabbri pilot is a small unit with relatively low-efficiency pumps and the projection of the data to a full-size plant with pumps of higher efficiency (HP: 75%; CP: 60%) is displayed in Fig. 2g2 and reveals an average specific energy of under 0.65 kWh/m^3. The reasons for the low energy consumption of the CCD technologies are evident from the data in Figs. 2g1 and 2g2 which demonstrate the progressively increased power needs of a consecutive sequential process on the timescale as a function of recovery.

4.2. Results of short Fabbri trials at 17.2 and 19.6 lmh of different maximum applied pressure

The short Fabbri trials, 3–4 h each, were performed by the same procedure used for the long trial described above (4.1) to ascertain the relationship between maximum applied pressure and maximum EC for recycled concentrates (brine) whereby it was made possible to estimate both recovery and silica concentration in brine. Trials were was performed under 17.2 and 19.6 lmh flux conditions with maximum applied pressure of subsequent trials raised stepwise, and a brine sample of each trial checked for clarity and EC. The temperature during the brief trials was found within the narrow range displayed in Fig. 2a, and the pH was controlled at the same level illustrated in this figure. Both series of short trials (17.2 and 19.6 lmh) were performed with the same cross-flow of CP displayed in Fig. 2b. The average Fabbri feed salinity during the short trials was found to be 1,850 µS/cm.

Results of the short Fabbri trials pertaining to EC of brine at maximum applied pressure of both series (17.2 and 19.6 lmh) are displayed in Fig. 3a, EC derived recoveries in Fig. 3b, and the brine silica content in Fig. 3c. The lower recovery at the same maximum applied pressure experienced for the 19.6 compared with the 17.2 lmh trials series revealed in Fig. 3b is consistent with theory in light of the net driving pressure (NDP) relationship NDP(17.2) < NDP (19.6) which implies the maximum applied pressure relationship $p_a(17.2) \approx p_a(19.6) - [\text{NDP}(19.6) - \text{NDP}(17.2)]$ for the same recovery, or osmotic pressure of brine, under CCD of fixed flow and variable flow conditions. In simple terms, the consistent trend displayed in Fig. 3b is in full compliance with theory.

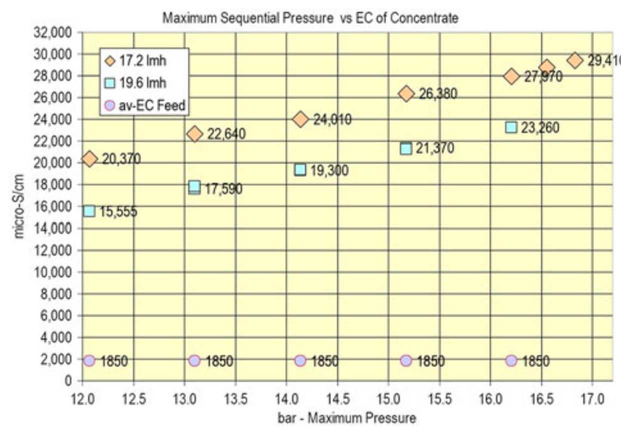

Fig. 3a. EC of brine as a function of maximum CCD applied pressure in the short Fabbri trials (3–4 h each) at 17.2 and 19.6 lmh.

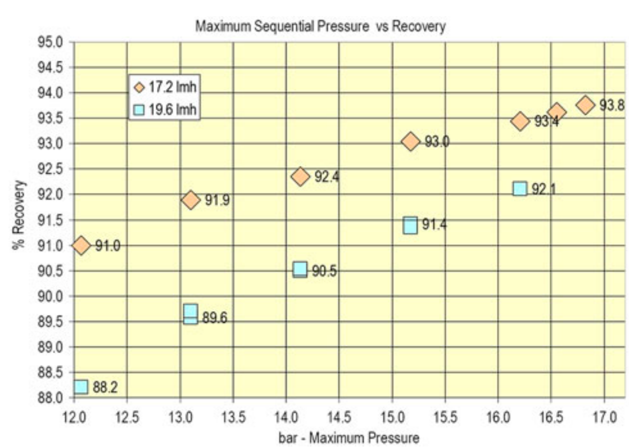

Fig. 3b. Recovery based on EC data as a function of maximum CCD applied pressure in the short Fabbri trials (3–4 h each) at 17.2 and 19.6 lmh.

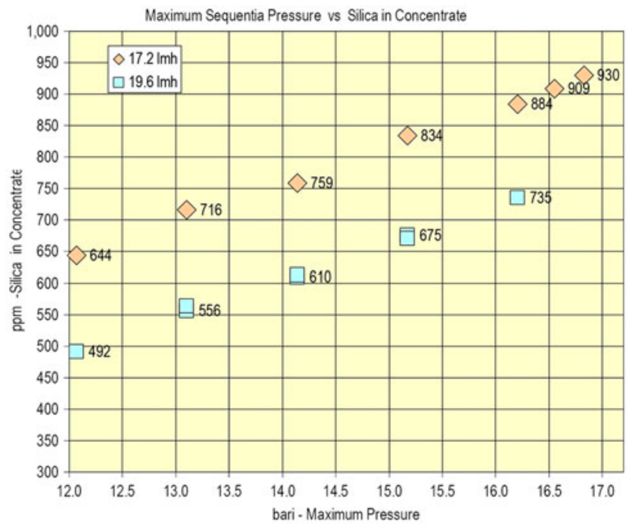

Fig. 3c. Silica content (ppm) in Brine as a function of maximum CCD applied pressure in the short Fabbri trials (3–4 h each) at 17.2 and 19.6 lmh.

In each of the short trials whose results are displayed in Figs. 3a–3c, the pattern of CCD minimum and maximum applied pressure, permeates EC, and module pressure difference remained essentially unchanged implying the absence of scaling and/or fouling and this was also supported by the clean brine samples retrieved for EC measurements. The maximum recovery based on EC of 93.8% observed during the short trials corresponds to silica concentration of ~930 ppm of exceptionally high supersaturation since the saturation of silica under normal conditions is in the 120–140 ppm range depending on pH and temperature [2]. The ability to reach relatively stable and extraordinarily high silica supersaturation during the short trials under review could be attributed to the low pH (~5.5), the dosing and effectiveness of the antiscalant (4.5–5.0 mg/l; FLOCON-260), and to the CCD technology of recycled concentrates and their dilution with fresh feed at module's inlet.

5. Discussion

The Fabbri farm well-water source (TDS: 1,304 ppm; SiO_2: 57 ppm) is located in the California Central Valley, a region most notoriously known in the United States for its wells with silica contents as high as 60 ppm. Accordingly, the Fabbri well has one of the highest silica contents in California where certain crops require irrigation water of much lower silica content. The intent of the Fabbri site selection for pilot testing was to ascertain the prospects of the BWRO-CCD technology for high recovery applications for feed water of high silica content.

Silica in well-water supplies is generally found in several different forms including insoluble colloidal and suspended particles (e.g. sand), and a soluble silica part of which is called reactive silica since it reacts with standard molybdate in a colorimetric test. The chemistry of this system is complicated further by the reactive silica interaction with water to produce monosilicic acid (H_4SiO_4) by an equilibrium which is pH and temperature dependent. Moreover, diatom species of algae assimilate reactive silica and use it to create a protective shell, and when the algae cells decompose, active silica is released again, some in a colloidal form, thereby, increasing the complexity of the process. The chemistry of silica is beyond the scope of this study, so the term silica used hereinafter is mainly the context of soluble silica irrespective of its forms.

A recent US patent application [14] entitled "Sea water reverse osmosis system to reduce concentrate volume prior to disposal" describes a noteworthy application of an open circuit desalination (OCD) of BWRO brine effluents (TDS > 10,000 ppm; silica > 125 ppm) with 80–85% recovery, using a single-element module conventional SWRO apparatus operated as batch under fixed applied pressure (e.g. 700–740 psi) of declined flux at low pH (e.g. 3–5) with an effective antiscalant (Pretreat Plus-0400). Apart from high silica, the source examined in this OCD study [14] also contained some other known scaling constituents (e.g. Ca > 4,000 ppm; Ba > 2.0 ppm and SO_4 > 7,400 ppm), and therefore, the demonstrated high recovery of this source implies an effective procedure for volume reduction at large, not only with respect to silica. The OCD process was reported to proceed in batch sequences, 20–30 min each, without any detectable scaling and this implied the ability to temporarily stabilize high supersaturation of silica (>1,000 ppm silica) under the specified conditions of low pH with an effective antiscalant at 25˚C. Despite the impressive results of the OCD procedure, its commercial applications are somewhat doubtful in light of high energy consumption and low productivity as a result of long batch sequences of declined flux with single-element modules. A plausible approach to overcome the limitations of the OCD procedure was conceived through CCD and in this context, a theoretical model study [15] with single-element modules under equivalent conditions of fixed pressure and variable flux revealed that the latter process proceeds with greater facility and dramatically lower energy consumption compared with the former. Another theoretical study [16] which compared seawater CCD desalination with single-element modules under variable pressure of fixed flux and under fixed pressure of variable flux conditions revealed enormous energy benefits for the former process. In light of the aforementioned, this study incorporated the conditions (e.g. low pH and effective antiscalant) for silica high supersaturation revealed by the OCD study [14] with the benefits of operating under CCD conditions of fixed flow and variable pressure conditions [15,16] using a three-element module configuration, instead of one, in order to affect greater productivity with lower installation costs.

The results of the current study shown in Figs. 2a–2g2 and Figs. 3a–3c reveal that an unmistakable high recovery of up to 93.8% of a silica-rich source (57 ppm) with CCD under fixed flow and variable pressure conditions using a module with three elements is indeed possible. A prospective role of such a technology for volume reduction applications at large is suggested. The current study fully supports the observations [14] of silica high supersaturation in RO under low pH which could be due to the greater effectiveness of antiscalant under such conditions. The pH effect during the course of the current study was realized when the acid dosing pump failed in the middle of one of the trials, when the pH rose over 7.0, and immediately soon after the minimum applied pressure started to rise with declined TDS of permeates, but without change of Δp, suggesting fouling by the creation of a thin silica film on membrane surfaces. CIP attempts at high pH (~11) to remove the created silica film enabled to initially restore the minimum applied pressure and TDS of permeate of the original experimental set point conditions, however, soon after rapid fouling started again suggesting that the membranes' fouling propensity increased beyond repair.

Feed quality with respect to particulate matter and TOC appears to be an important factor for successful CCD performance with high supersaturation of silica, since failures of the media-filtration and/or micronic filter and/or TOC removal means to supply sufficiently adequate quality feed led within a short period of time to membrane fouling without scaling in the absence of detectable change of Δp. The aforementioned observations are consistent with the reported OCD trials [14] where the turbidity of feed was maintained at 0.3 NTU.

6. Concluding remarks

The CCD experimental results of this study with a pilot comprising a single module of three elements revealed exceptional high recovery (93.8%) of a silica-rich feed source (57 ppm) at low pH (~5.5) in the presence of antiscalant (4.5–5.0 ppm; FLOCON-260) under silica supersaturation conditions as high as 930 ppm, just under the maximum reported value (~1,000 ppm) for OCD [14] with a single-element module under a lower pH (2–5). This may suggest the prospects of an even higher recovery by CCD with the Fabbri source at a lower pH (3–5). In contrast with the reported OCD technology [14], CCD offers greater productivity, much lower energy consumption, greater performance flexibility, and reduced fouling prospects in light of the dilution effect of the recycled concentrates with fresh feed at inlets to modules. Recovery of CCD is not confined by the number of elements per module but only by the scaling constituents of the source and such constituents in the brine of the Fabbri source at 93.8% recovery include 4,516 ppm Ca; 19.35 ppm Sr; 6,129 ppm SO_4; and 919 ppm SiO_2. In light of the limited solubility of $CaSO_4$ (~2.0 g/L) and $SrSO_4$ (~0.1 g/L), the results of the Fabbri trial of 93.8% recovery imply desalination under high supersaturation of cited salts apart from silica and the prospective use of CCD for volume reduction applications at large.

Acknowledgments

Funds to Desalitech Ltd. by Aquagro Fund L.P. (Israel) and by Liberation Capital LLC (USA) and Spring Creek Investments (USA) are gratefully acknowledged.

References

[1] Silica (SiO_2). Available from: <http://en.wikipedia.org/wik/silcon_dioxie>.
[2] Silica Scale Prevention, Dow Liquid Separation, FILMTEC™ Reverse Osmosis Membranes, Technical Manual, 2011, pp. 4–50. Available from: <http://msdssearch.dow.com>.
[3] Z. Amjad, R.W. Zuhl, The role of water chemistry on preventing silica fouling in industrial water systems", paper no-10048, NACE Corrosion 2010 Conference & Expo, San Antonio, Texas, USA, 14–18 March, 2010..
[4] System Design, Dow Liquid Separation, FILMTEC™ Reverse Osmosis Membranes, Technical Manual, 2011, pp. 72–102. Available from: <http://msdssearch.dow.com>.
[5] A. Efraty, Closed circuit desalination series no-9: Theoretical model assessment of the flexible BWRO-CCD technology for high recovery, low energy and reduced fouling applications, Desalin. Water Treat. 53(7) (2015) 1755–1779.
[6] Z. Gal, J. Septon, A. Efraty, A.-M. Lee, CCD Series no-20: High flux low energy upgrade of municipal water supplies with 96% recovery for boiler-feed and related applications, Desalin. Water Treat. (in press).

[7] A. Efraty, J. Septon, Closed circuit desalination series no-5: High recovery, reduced fouling and low energy nitrate decontamination by a cost effective BWRO-CCD method, Desalin. Water Treat. 49 (2012) 384–389.
[8] J. Septon, A. Efraty, CCD Series No-17: Application of the BWRO-CCD technology for high recovery low energy desalination of domestic effluents, Desalin. Water Treat. (in press), doi: 10.1080/19443994.2015.1035498.
[9] B. Mnasell, T. Nikonova, P. Ackman, B. Langpap, C.C. Tang, R. Tremblay, P. Friess, Evaluation of RO concentrate treatment and disposal options or the Santa Clarita Valley, 29th Annual WateReuse Symposium, Dallas, TX, September 7–10, 2014.
[10] 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.
[11] A. Efraty, Closed circuit desalination series no-3: High recovery low energy desalination of brackish water by a new two-mode consecutive sequential method, Desalin. Water Treat. 42 (2012) 256–261.
[12] A. Efraty, Z.l. Gal, Closed circuit desalination series No 7: Retrofit design for improved performance of conventional BWRO system, Desalin. Water Treat. 41 (2012) 301–307.
[13] ESPA2-MAX Membrane Specification. Available from: <http:/www.membranes.con/8inch/ESPAE%MAX.pdf>.
[14] A.J. Tarquin, Sea water reverse osmosis systems to reduce concentrate volume prior to disposal, US Patent Application, Pub. No.: US 2011/0036775 A1.
[15] A. Efraty, CCD Series No-16: Opened versus closed circuit SWRO batch desalination for volume reduction of silica containing effluents under super-saturation conditions, Desalin. Water Treat. (in press), doi: 10.1080/19443994.2015.1035494.
[16] A. Efraty, CCD Series No-14: SWRO-CCD under fixed-pressure and variable flow compared with fixed-flow and variable pressure conditions, Desalin. Water Treat. 56(4) (2015) 875–893.