Desalination and Water Treatment
www.deswater.com

41 (2012) 301–307
March

doi: 10.1080/19443994.2012.664716

Taylor & Francis
Taylor & Francis Group

Closed circuit desalination series No 7: retrofit design for improved performance of conventional BWRO system

Avi Efraty*, Zviel Gal

Desalitech Ltd., P.O. Box 132, Har Adar, 90836, Israel
Tel. +972 52 4765 687; Fax: +972 2 5700262; email: avi@desalitech.com

Received 4 October 2011; Accepted 26 December 2011

ABSTRACT

Improved performance of conventional brackish water reverse osmosis (BWRO) technology is achieved by the integration with the newly conceived closed circuit desalination (CCD) technology of low energy consumption without need of energy recovery, low scaling and fouling characteristics, high recovery irrespective of number of elements per modules, wide range operational flux, and flexible control of membranes and modules performance in compliance with manufacturers' specifications. The present article describes the application of a retrofit system for 88.5% desalination of a feed source (6,500 μS/cm) whereby permeate (324 μS/cm) was obtained with reverse osmosis energy consumption of 0.555 kWh/m^3 and an overall energy consumption of 0.609 kWh/m^3—these results were unattainable by a full-scale conventional BWRO desalination complex which operated adjacent to the retrofit unit with the same feed source. The retrofit unit under review utilizes the pressurized brine flow from a conventional BWRO pass of 50% recovery as feed into a CCD system with modules of four elements each; wherein, the recovery is raised to the desired level under consecutive sequential conditions of fixed flow and variable pressure with continuous production of permeates. The new retrofit technology could apply to any existing conventional BWRO plant of high scaling and/or fouling characteristics by the conversion of the second stage of such a plant into a close circuit desalination system of short modules and flexible control; wherein, scaling and/or fouling effects are reduced substantially or completely eliminated.

Keywords: Closed circuit desalination; High recovery; Low energy; Reduced fouling; Brackish water; Improved BRWO systems

1. Introduction

Conventional brackish water reverse osmosis (BWRO) is extensively used commercially for diverse applications including brackish water desalination, upgrade of domestic supplies, decontamination of drinking water, high quality water production, removal of Boron from 1st pass sea water reverse osmosis (SWRO) permeates, treatment of industrial and/or of domestic effluents, medical dialysis, and many additional applications less common. A typical conventional BWRO system comprises pressure vessels with six elements arranged in staged arrays of modules with inter-stage booster(s) to enable sufficient flow and pressure along the line of membranes for high reverse osmosis (RO) recovery with low energy consumption. A two stage BWRO system is normally recommended for recovery up to 75% and a three stage system for recovery up to 88%, with exact design depending on the salinity of the source and the nature of its

*Corresponding author.

constituents. The existing BWRO systems allow limited control of membrane performance with increased tendency of scaling and fouling normally associated with tail elements and with front elements fouling probability increased when flow and pressure conditions at inlet exceed test conditions specifications of manufacturers in order to improve recovery and/or quality of product. Scaling and fouling development in commercial BWRO systems require frequent CIP procedures with increasing loss of production and with ultimate need to replace membranes, all of which manifest considerable expenses and lose of revenues. Scaling and fouling problems experienced in the operation of commercial BWRO systems are greatly enhanced in cases of large variation in the salinity of sources and their constituents.

Closed circuit desalination (CCD) is a newly conceived versatile technology of low energy consumption without need of energy recovery, high recovery irrespective of number of elements per modules, wide range operational flux, flexible control means of membranes performance in order to meet their manufacturing specifications, and low scaling and fouling characteristics. In contrast with conventional plug flow desalination (PFD), the CCD technology uses short modules (3/4 elements per module) and concentrates recycling means and the accumulated brine in the closed circuit is occasionally replaced by fresh feed at the desired system recovery level without stopping desalination. The three principle configurations of the CCD technology reported thus far are described in the patent literature [1–3], their commercial applications are reported for sea water [4,5] and brackish water [6–8] and the comparison between CCD and PFD reviewed [9].

The present article describes the application of the new retrofit technology [3] for high recovery (~88.5%) production of quality permeates (average 324 μS/cm) from a relatively high salinity feed source (6,500 μS/cm) with low RO energy (0.55 kWh/m^3), by a single apparatus located in the backyard of the large Maagan Desalination Plant; wherein, such results are unattainable even with the aid of several independent units. The results described herein clearly suggest the viable option of the retrofit technology to improve the performance of inferior BWRO units worldwide.

2. The retrofit system design

The Maagan Michael Retrofit design displayed in Fig. 1 comprises three principle sections, the so-called RO-1 (PFD), RO-2(CCD) and side conduit (SC). The labels in the design are V(1, 2, ..., 7) for electrically actuated two-way valves; CV for a check valve; HP

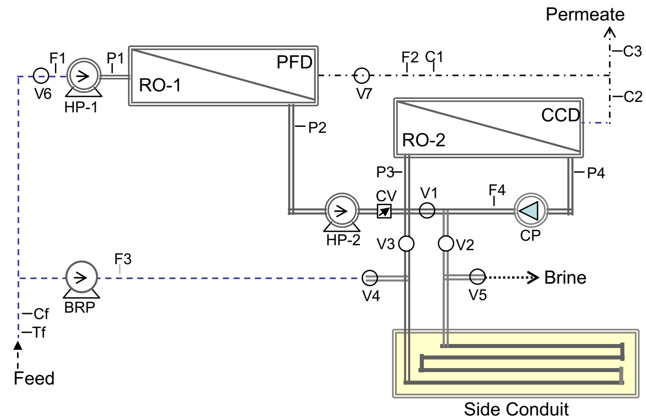

Fig. 1. The PFD–CCD retrofit unit at Maagan Michael for 55 m^3/h.

for high pressure pumps with *vfd*; CP for a circulation pump with *vfd*; C for electric conductivity monitors; F for flow meter (or water meter) monitors; P for pressure transmitters; T for a temperature monitor of feed; and Cf for a conductivity monitor of feed. The RO-1 section comprising a single array of a conventional PFD design with five pressure vessels (8″—660 cm), each of six RE8040-BE4O0 membrane elements, fed by HP-1 at a desired flow rate Set Point (SP) controlled by the flow meter F1 through the throttle valve V6, with the desired desalination recovery attained through the SP of permeate flow controlled by the flow meter F2 and the throttle valve V7—the above mentioned SP of flow also dictates the flow rate of brine in view of the flow balance Eq. (1); wherein, the subscript f stands for feed, p for permeate and b for brine with a number to identify the RO-1 section. The fixed flow of pressurize brine from RO-1 is passed through the fixed flow variable pressure pump (or booster) HP-2 and the check valve CV into the so-called RO-2 section of seven pressure vessels (8″—660 cm), each of four RE8040-BE440 membrane elements, with their inlets and outlet connected in parallel by conduits and a circulation pump (CP) to enable recycling of concentrate from outlet to inlets of modules at a fixed desired flow rate SP (cross flow) controlled by the flow meter F4 and the *vfd* of the pump with the entire process in this section taking place in consecutive sequential steps under CCD conditions according to the flow balance expressed by (2) and with occasional brine rejection as is explained next. Brine replacement with fresh feed in RO-2 without stopping desalination takes place by the occasional engagement/disengagement of a SC by means of actuated valves (V1–V5) and connecting lines according to the schematic design in Fig. 1. The SC section comprises four pressure vessels (8″—860 cm) connected in line with intrinsic volume (V) of 1,066 L compared with 1,060 L in the closed circuit of RO-2. The engagement is initiated at a defined SP of maximum CCD pressure, or alternatively at a defined maximum electric conductivity of recycled concentrate, which manifests the attainment of the desired system recovery level; and terminated (disengagement) after the defined SP of brine volume in RO-2 (1,060 L) is replaced by fresh pressurized feed through the engagement with the SC which is nearly of the same intrinsic volume (1,068 L). The recovery (R) of the entire system under review is expressed by (3), assuming Q expressed in m^3/h; wherein, Q_{p1} and Q_{p2} stand for permeate production in the respective units RO-1 and RO-2, Q_f for feed flow at inlet to RO-1, and N for the number of SC engagement per hour each involving the replacement of V m^3 of brine by fresh feed.

$$Q_{f1} = Q_{p1} + Q_{b1} \quad (1)$$

$$Q_{b1} = Q_{p2} \quad (2)$$

$$\begin{aligned} R &= 100*(Q_{p1} + Q_{p2}/(Q_f + N*V) \\ &= 100*(Q_{p1} + Q_{p2})/(Q_{p1} + Q_{p2} + N*V) \end{aligned} \quad (3)$$

The engagement/disengagement of RO-2 and SC, whereby brine in the closed circuit is replaced by fresh feed at the desired system recovery level without any loss of energy, proceeds by the actuation of valves at selected SPs during the continuously monitored and controlled process. The position of the system displayed in Fig. 1 is that of a disengaged system (V1 open and V2 and V3 closed) with decompressed SC undergoing replacement of brine by fresh feed through the brine replacement pump (BRP) (V4 and V5 open) until the exact displaced volume SP monitored by F3 is attained; thereafter, the SC is sealed (V4 and V5 closed), decompressed (V2 opened), and left on stand-by until the next engagement which will take place by the simultaneous opening of V3 and closure of V1. Engagement/disengagement proceeds on a consecutive sequential basis and depends on the performance characteristics of RO-2 expressed by Eqs. (4)–(9); wherein, R_2 stands for recovery, v_2 for volume of permeate produced during a single sequence, V_2 for intrinsic volume of closed circuit; T_2 for sequence period; MR_2 for module recovery; Q_{CP} for concentrate recycling flow; $SE_{HP\text{-}2}$ for specific energy associated with HP-2 in RO-2; p_{av} for average sequential pressure in RO-2; $f_{HP\text{-}2}$ for efficiency ratio of HP-2 in RO-2; and SE_{CP} for specific energy associated with CP wherein Δp is the module pressure difference in RO-2 and f_{CP} the efficiency of said pump. The entire system recovery according to (3) requires the knowledge of Q_{p1}, Q_{p2}, Q_f, and V which are SP of control board as well as of N which can be determined either by (6) and (10), or from pertinent sequential data such as the variable sequential pressure and/or electric conductivity of permeate and/or electric conductivity of recycled concentrate in RO-2. Irrespective whether T_2 (min) is calculated from (6) or determined directly from the consecutive sequential performance data of RO-2, the number of sequence per hour is expressed by (10).

$$R_2 = [v_2/(v_2 + V_2)]*100 \quad (4)$$

$$\begin{aligned} &v_2 = Q_{f2}*T = Q_{p2}*T = Q_{b1}*T \\ &\text{Since } Q_{f2} = Q_{p2} = Q_{b1} \end{aligned} \quad (5)$$

$$\begin{aligned} T_2 &= R_2*V_2/[Q_{f2}*(100 - R_2)] \\ &= R_2*V_2/[Q_{p2}*(100 - R_2)] \\ &= R_2*V_2/[Q_{b1}*(100 - R_2)] \end{aligned} \quad (6)$$

$$\begin{aligned} MR_2 &= Q_{f2}*100/(Q_{f2} + Q_{cp}) = Q_{p2}*100/(Q_{p2} + Q_{CP}) \\ &= Q_{b1}*100/(Q_{b1} + Q_{CP}) \end{aligned} \quad (7)$$

$$SE_{HP} = p_{av}/36/f_{HP-2} \quad (8)$$

$$SE_{CP} = Q_{CP}*\Delta p/36/f_{CP}/Q_{P2} = Q_{CP}*\delta p/36/f_{CP}/Q_{b1} \quad (9)$$

$$N = 60/T_2 \quad (10)$$

The principle power components in Fig. 1 comprise the pumps HP-1, HP-2, CP, and BRP with their energy consumption monitored individually; thereby enabling precise energy count of the entire system and its components. The average RO energy of the entire system under review relates to the energy consumption by HP-1, HP-2, and CP; whereas, the overall energy consumption also takes account the energy consumption of the BRP and the client delivery pump (CDP) of permeate (not shown in Fig. 1) apart from the negligible energy needs of the control board and the actuated valves. The specific energy reported hereinafter is based on energy metered data and pertain to average RO energy for the entire system as well as to the overall irrespective of nature of consumption.

3. Results and discussion

Feed to the system depicted in Fig. 1 with view in Fig. 2 (henceforth "retrofit") was received from the Maagan Desalination Plant located on the sea shore about half way between Tel Aviv and Haifa in Israel. The source comprising a blend derived from some 16 brackish water wells in the vicinity of the plant with an average salinity of the blend manifested by electric conductivity in the range of 6,000–6,800 μS/cm. Pre-treatment of the supply source is done only by micronic filter (1.0 μ) and as added safe guard against suspected colloidal silica, an additional micronic filter (0.5 μ) was installed at inlet to the retrofit. Anti-scaling agent (Flocon-260) was mixed with the feed to the retrofit at a rate of 2.0 mg/L. The results reported hereinafter are the internet collected actual monitored performance data on 18 July 2011 over the time interval 11:00–12:00 by the fully automated retrofit system which is equipped with remote control operations means. The operational SPs of the retrofit during said data collection period were as followed: $Q_f = 55.0\,m^3/h$; $Q_{b1} = Q_{f2} = 27.5\,m^3/h$ (50% recovery of RO-1); $Q_{CP} = 30.0\,m^3/h$; 27 bar maximum sequential pressure in RO-2; 1,060 L of displaced brine volume from RO-2 during engagement; and 1,200–1,300 L of displaced brine volume from disengaged SC.

The monitored data of the retrofit are fully consistent with the dictated SP of operation which manifests 47.8% MR and ~15% head element recovery during the CCD sequences in RO-2, and these selected membranes performance parameters are within the test conditions recommendations by the membrane manufacturer. Actual flow data pertaining to feed (Q_{f1}) into RO-1; recycled concentrate in RO-2 (Q_{CP}); RO-1 permeate (Q_{p1}); and RO-2 permeate (Q_{p2}) is furnished in the respective figures Figs. 3–6 over the same time period interval. The flow rate of permeate production in RO-2 which is displayed in Fig. 6 also represents the feed flow into RO-2 and the brine flow from RO-1, since $Q_{f2} = Q_{p2} = Q_{b1}$. The actual monitored results show small variability around the SPs which most probably reflects the response time through the control required in order to adjust for the fixed flow variable pressure operational conditions of RO-2. The small flow variability of permeate production in RO-2 according to Fig. 6 reveals a pattern consistent with the consecutive sequential pressure variations in the system; therefore, confirming the *vdf* effects created under the fixed flow and variable pressure conditions. Concentrate recycling selection as displayed in Fig. 4

Fig. 2. View of the PFD–CCD retrofit unit at Maagan Michael.

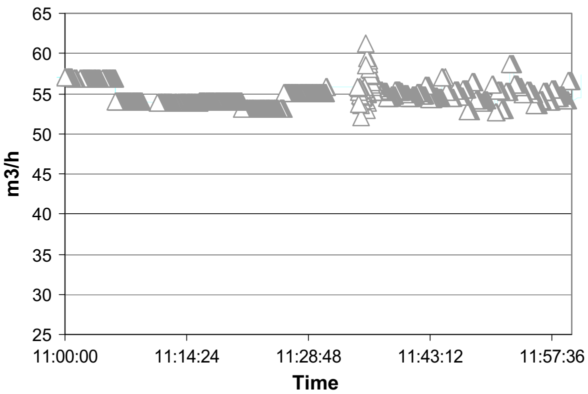

Fig. 3. Feed flow into RO-1.

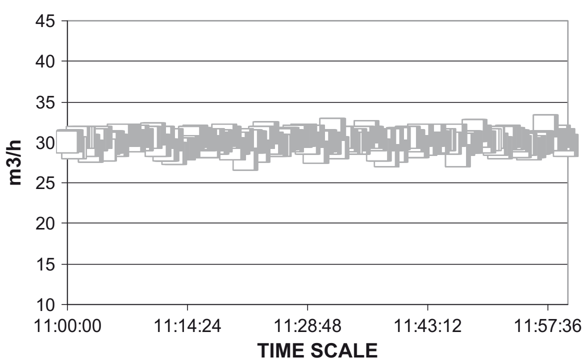

Fig. 4. Recycled concentrate flow in RO-2.

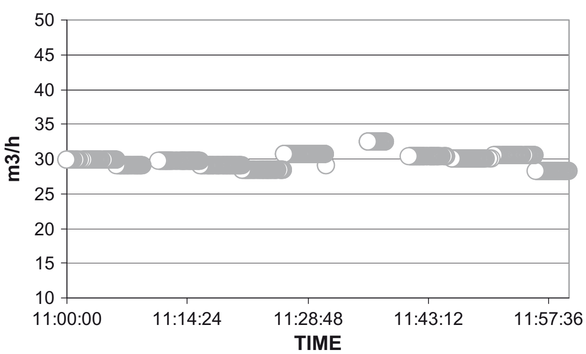

Fig. 5. Permeate flow from RO-1.

is another noteworthy feature of the CCD technology which enables control of concentration polarization and the attainment of the desired MR and head element recovery irrespective of flux. The combination of PFD and CCD according to the retrofit design in Fig. 1 provides a viable concept from the stand point of the flow balance of the individual components displayed in Figs. 3–6.

The pressure operation of the retrofit system in Fig. 1 depends on the stage in the process with

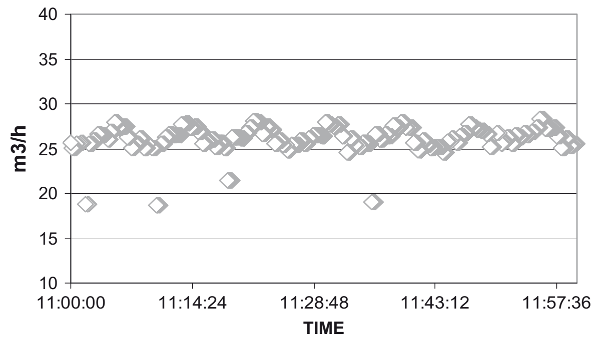

Fig. 6. Permeate flow from RO-2.

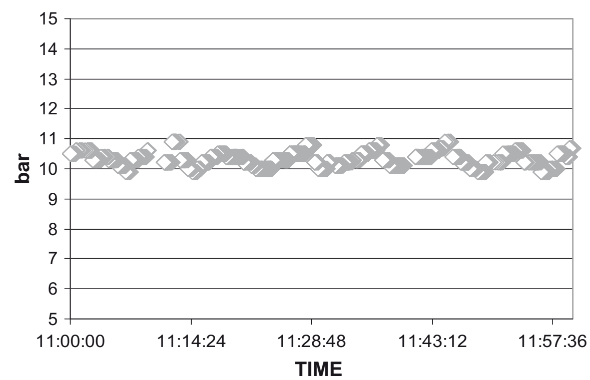

Fig. 7. Pressure of RO-1.

pressurized feed (2.5 ± 0.5 bar) received at inlet to HP-1; pressurized brine from RO-1 used as pressurized feed to RO-2 (10.5 ± 0.5 bar—Fig. 7); and consecutive sequential pressure variation in RO-2 (range: 11–27 bar—Fig. 8) created by HP-2 under fixed flow ($27.5\,m^3/h$) conditions of feed and permeate alike. The pattern of small sequential pressure variations revealed in Fig. 7 for RO-1 most probably relates to the fixed flow and variable pressure (Fig. 8) operation of RO-2. The monitored pressure difference of modules in RO-1 (0.7 ± 0.10 bar) and RO-2 (0.45 ± 0.15 bar) pertains to modules with six and four membrane elements, respectively, with a greater difference expected with more elements. The average CCD sequence period (T_2) experienced in RO-2 according to Fig. 8 is 8.9 min/sequence or 6.74 (=N) sequences per hour. The SP determined and experimentally confirmed average flow rates Q_{f1}, Q_{p1}, and Q_{p2} together with $N = 6.74$ sequences/hour and $V = 1.06\,m^3$ for the closed circuit intrinsic volume of RO-2, yield an overall RO recovery of 88.5% for the retrofit in the trial under review according to (3).

The performance of the retrofit was also characterized on the basis of certain electric conductivity (EC)

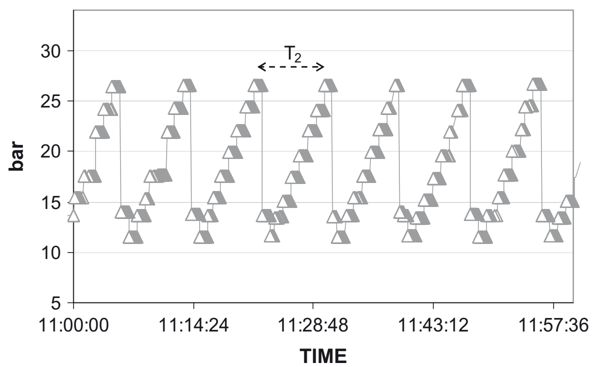

Fig. 8. Pressure variations in RO-2.

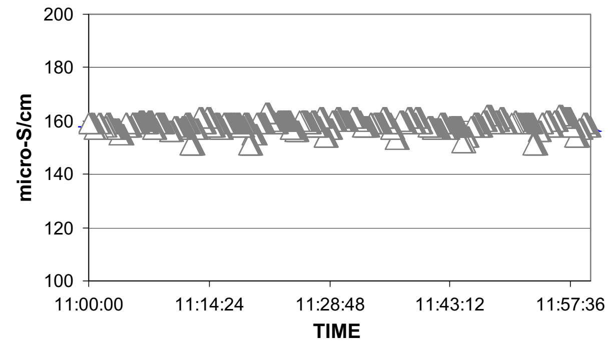

Fig. 10. EC permeate RO-1.

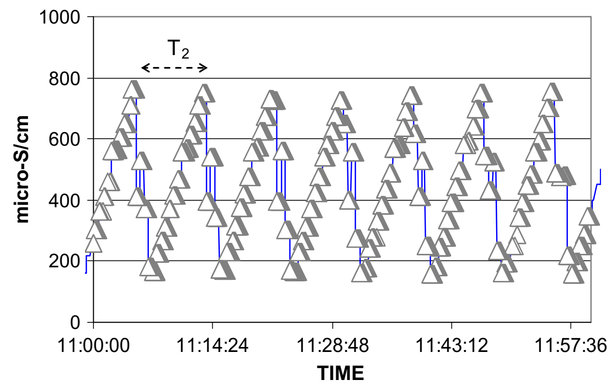

Fig. 11. EC permeate RO-2.

parameters measured for the feed supplied to RO-1 (Fig. 9), the permeates of RO-1 (Fig. 10) and RO-2 (Fig. 11). The supplied feed during the trial was of fixed EC (6,500 μS/cm). The average EC of permeates under trial conditions of 158 μS/cm for RO-1 and 490 μS/cm for RO-2 (range 190–790 μS/cm) together with equivalent flow rates of 27.5 m^3/h, imply permeate production of 55 m^3/h with blend EC of 324 μS/cm or TDS ≈ 162 ppm of which about half is chloride (assuming same ratio of Cl and TDS in source and permeates). The large EC variations of produced permeate during consecutive sequential operation of RO-2 displayed in Fig. 11, reflect increased salinity of recycled concentrate on the time scale of the sequence. The sequential EC pattern in Fig. 11 is essentially the same as that associated with pressure variations in Fig. 8 with both showing the same value of T_2 (8.9 min/sequence) and of N (6.74 sequences/h). The term N accordingly to (10) is inversely proportional to T_2 and the latter, according to (6), depends on the intrinsic volume of RO-2 (V_2), the flow rates $Q_{f2} = Q_{p2}$ and the R_2 recovery. In simple terms, the entire retrofit system recovery (R) which is expressed by (3) depends only on Q_{f1} (inlet feed flow to retrofit), N, and T_2, irrespective of any of the operational parameters associated with the SC and/or the BRP.

The power consumption of the Maagan retrofit was monitored continuously for the different pumps in the system, with other pertinent information on pumps' performance obtained from the monitored flow and pressure data. The entire information related to energy consumption and pumps performance over the period of the trial under review is furnished in Table 1 with clear distinction made between RO-related and none-related operations. The specific energy (SE) of RO-related operations takes account of flow, pressure, and metered energy of RO-1 and RO-2 with regard to HP-1(0.368 kWh/m^3), HP-2 (0.164 kWh/m^3) and the recycled concentrate pump CP (0.023 kWh/m^3) of 0.555 kWh/m^3 total. None of the RO functions in the retrofit under review include the BRP (~0.027 kWh/m^3) and the CDP (~0.027 kWh/m^3). The total SE consumption counting both RO-related and none-related operations is 0.609 kWh/m^3 and this figure does not take into an account the feed pressure at inlet to retrofit. The pressurized (2.5 bar) feed (62.1 m^3/h = 55 m^3/h HP-1 = 7.14 m^3/h BRP) supplied to the retrofit translates to 155.2 bar m^3/h or

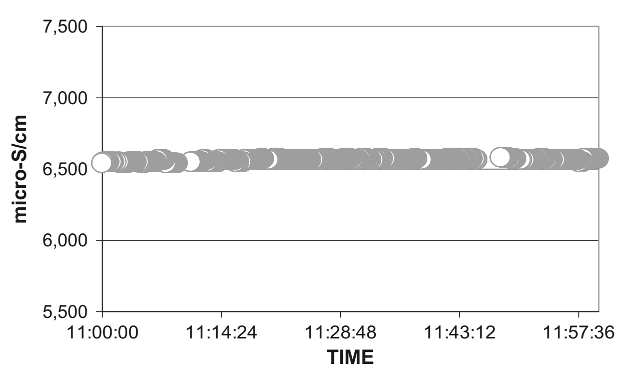

Fig. 9. EC feed to RO-1.

Table 1
Maagan retrofit power demand on 18/07/2011 10:00–11:00

Item	RO operations				None RO functions		
	HP-1	HP-2	CP	Total	BRP	CDP	Total
Meter, kWh/h	20.25	9.00	1.25	30.50	1.50	1.50	3.00
Feed, m^3/h	50.55	27.50	30.00				
Pump inlet, bar	2.50	10.50					
Average pump outlet, bar	10.50	19.00					
Pump effective, bar	8.00	8.50	0.45				
Pump % efficiency	60.36	72.15					
Total permeate	55.00	55.00		55.00	55.00	55.00	55.00
Special energy, kWh/m^3	0.368	0.164		0.555	0.027	0.027	0.055

Notes: Grand total; of all components (HP-1; HP-2; CP; BRP; CDP) = 0.609 Kwh/m^3.
CP, circulation pump; BRP, brine replacement pump; CDP, cilent delivery pump.

4.312 kWh or 0.078 kWh/m^3; therefore, the entire SE consumption of the process is 0.687 kWh/m^3.

4. Concluding remarks

The performance of the Maagan Retrofit is self-evident from the displayed results of which noteworthy in particular are the high recovery (88.5%), the low RO energy (0.555 kWh/m^3), and the quality permeates (average 314 μS/cm) production under conditions of low scaling and fouling characteristics. None of the conventional units in the Maagan Desalination Plant, or anywhere else, were ever reported to enable similar results with a complete process control of low fouling characteristics. The superb performance of the retrofit unit at Maagan was found to be unmatched by the conventional RO which operated at the same site with the same feed source. The retrofit design of conventional BWRO systems may involve, for example, the conversion of the second stage into a CCD system, or by many other design options. The improved performance of a conventional system by means of a CCD retrofit should enable increased production availability with lower energy costs and reduced operational expense due to decreased scaling and fouling factors with lesser need for CIP procedure and the aforementioned imply a short investment return of the retrofit installation costs.

Acknowledgments

The authors wish to thank Maagan Desalination for granting permission to operate the retrofit unit in its backyard; to Mr. Y. Berchman for his help, assistance and patient, and to AQUAGRO FUND L.P. for financial support.

References

[1] A. Efraty, Apparatus for continuous closed circuit desalination under variable pressure with a single container, US Patent No. 7628,921 and related patents issued worldwide.
[2] A. Efraty, Continuous closed circuit desalination apparatus without containers, US Patent No. 7695,614 B2 and related patents issued worldwide.
[3] A. Efraty, PCT International Publication No. WO/2011/004364, entitled "Closed circuit desalination retrofit for improved performance of common reverse osmosis system", 13.01.2011.
[4] A. Efraty, N.R. Barak, Z. Gal, Closed circuit desalination—a new low energy high recovery technology without energy recovery, Desalin. Water Treat. 31 (2011) 95–101.
[5] A. Efraty, N.R. Barak, Z. Gal, Closed circuit desalination series No.-2: New affordable technology for sea water desalination of low energy and high flux using short modules without need of energy recovery, Desalin. Water Treat. (in press).
[6] 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. (in press).
[7] 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. (in press).
[8] 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. (in press).
[9] A. Efraty, Circuit desalination series No.-6: Conventional RO compared with the conceptually different new closed circuit desalination technology, Desalin. Water Treat. (in press).