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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

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ABSTRACT

Brackish Water sources of 6800 and of 4000 μS cm^{-1} were desalinated in closed circuit by single stage consecutive sequential process with 80% and 88% recovery, respectively, using an apparatus comprising eight modules (8″), each of four elements (ESPA2+), with their inlets and outlets connected in parallel, wherein recycled concentrate mixed with fresh pressurized feed admitted at inlet to modules. The exemplified apparatus, named REIM-I, was operated with fixed permeate flow under variable pressure conditions and the brine in the closed circuit was occasionally replaced by fresh feed through the engagement a side conduit and this without stopping desalination and without any energy loss. The operation of the REIM-I unit is exemplified with 80% recovery of a high salinity (6,800 μS cm^{-1}) feed source at fixed flux of 19 lmh; fixed permeate flow of 24.4 m^3 h^{-1} (586 m^3 d^{-1}) of an average 625 μS cm^{-1} conductivity; a variable pressure range of 11–22 bar with an average of 17.7 bar, and an overall specific energy consumption of 0.82 kWh m^{-3} with high pressure pump efficiency of ≈55%. The operation of the REIM-I unit is also exemplified with 88% recovery of a medium salinity (4000 μS cm^{-1}) feed source remove off at fixed flux of 27 lmh; fixed permeate flow of 35.0 m^3 h^{-1} (840 m^3 d^{-1}) of an average 482 μS cm^{-1} conductivity; a variable pressure range of 12–21 bar with an average of 16.2 bar, and an overall specific energy consumption of 0.80 kWh m^{-3} with high pressure pump efficiency of ≈60%. The new technology under review, which enables the attainment of any desired recovery made possible by the constituents of the source in the presence of suitable anti-scaling agents without any loss of brine energy, has been operated commercially for the past two years continuously providing some 400,000 m^3 of permeates under 1300 μS cm^{-1} for irrigation in the dry Negev district of Israel. The application of the new technology for Brackish Water desalination of high recovery and low energy, reported herein for the first time, was recently demonstrated to allow desalination of Mediterranean Water (4.1%) with a record low RO energy (1.85 kWh m^{-3}, 13 lmh flux, and 85% efficiency of high pressure positive displacement pump) which manifests energy saving of ≈30% compared with the reported RO energy consumption of large desalination plants equipped with modern energy recovery means.

Keywords: High salinity brackish water; Closed circuit desalination with a side conduit; Low energy without energy recovery; High recovery; Reduced fouling; Commercial unit performance

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Closed Circuit Desalination (CCD) is a unique batch desalination process of enormous energy efficiency benefits [1–3] and the making of such a process continuous with respect to permeate production by simple mean [4] opened the door to its commercial application. The first paper in this series [5] describes the theoretical principles of CCD and exemplifies the process with SWRO-CCD trials carried out with Mediterranean Water (4.1%) using an apparatus with four modules (M) each of four elements (E) – 4ME4 configuration. The trials results revealed RO energy of 1.85–2.25 kWh m^{-3} for 47.5 ± 1.5% recovery in the respective flux range 6–18 lmh with head element recovery of 7.0 ± 0.5%. The extraordinary energy results received using the SWRO-CCD new method for Mediterranean Water desalination were found much lower compared with the best results obtained by conventional SWRO techniques with the most advanced energy recovery means. The second paper in this series [6] describes SWRO-CCD Mediterranean trials using the 4MEn apparatus of four different configurations (n = 1–4) which revealed the RO energy range 1.8–2.8 kWh m^{-3} in the respective flux range 8–40 lmh for recovery up to 50%. Mediterranean trials RO energy of the new technology at flux of 13–14 lmh of conventional SWRO plants was found in the range 1.9–2.1 kWh m^{-3} with a plausible further improvement to 1.7–1.8 kWh m^{-3} expected if the feed pressurizing and concentrate recycling means could be operated with 85% and 60% efficiency, respectively.

The present report describes the application of the CCD technology to Brackish Water feed of 6800 and of 4000 μS/cm salinity using a BWRO-CCD 8ME4 apparatus of the schematic design displayed in Fig. 1. The design displayed in Fig.1 shows the closed circuit RO section and the disengaged side conduit section which undergoes brine replacement by fresh feed; wherein, *HP* stands for the high pressure pump, *CP* for circulation pump, *BRP* for the brine replacement pump, *PV* for empty pressure vessels side conduit (8″–300 psi rating), *M* for modules (8″–300 psi rating), *E* for ESPA2+ membrane elements, 1–4 for the main actuated valves (3″), and 5–6 for the compression/decompression (1/2″) valves of the side conduit. The continuously monitored data included FLOW & ELECTRIC CONDUCTIVITY (EC) of feed, permeate and recycled concentrate; PRESSURE at inlet and outlet of modules; pH of feed and permeate; and the ENERGY CONSUMPTION of each of the pumps separately. All the trials reported herein were carried out under fixed flow conditions with constant flow rates of relevant pumps (HP and CP) controlled by means of *vfd* through the appropriate flow meters. BWRO-CCD is a consecutive sequential technology which enables periodic engagement of the principle RO system with a side conduit of the same intrinsic volume by means

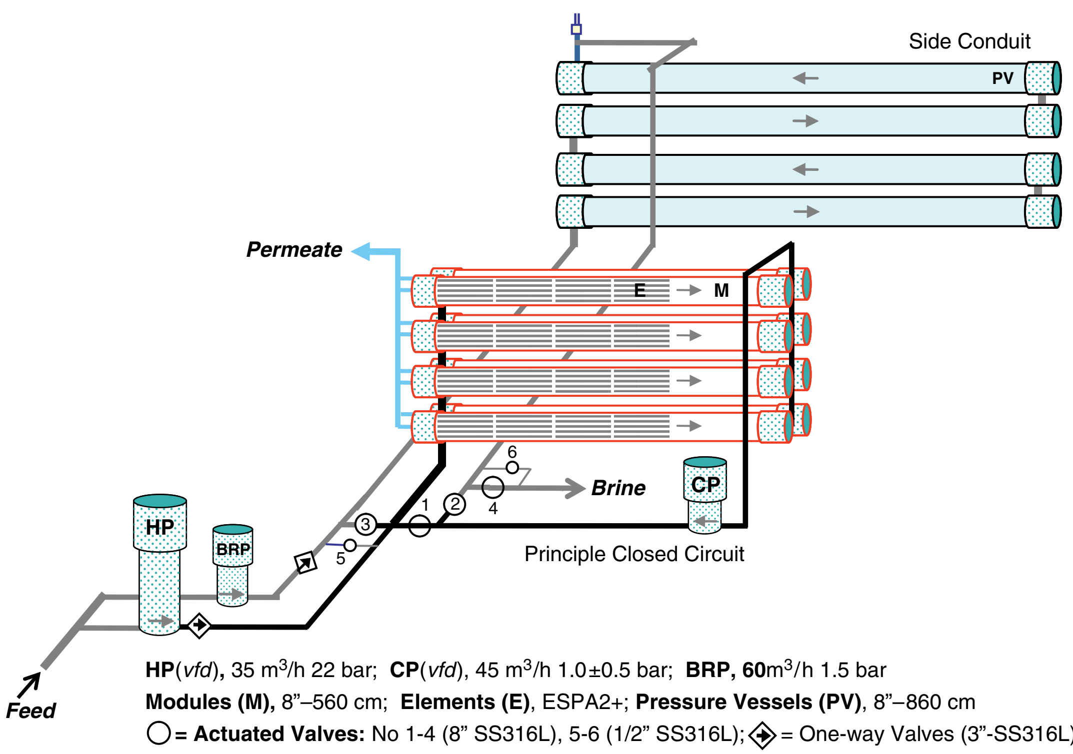

Fig. 1. The schematic design of the BWRO-CCD 8ME4 unit.

of actuated valves, a process whereby brine is replaced by fresh feed without stopping desalination. Initiation of engagement takes place at a selected maximum conductivity set point (SP) of the recycled concentrate which manifests the attainment of the desired system recovery by the principle closed circuit. Accordingly, higher maximum conductivity SP is concomitant with higher system recovery and vice versa. Disengagement of the principle closed circuit from the side conduit and resumption of CCD is initiated by a volume meter signal manifesting the replacement of the desired volume of brine by fresh feed. After disengagement from the principle closed circuit, the side conduit is decompressed, its brine content replaced by fresh feed using a pump (BRP), and than, the freshly charged side conduit is compressed and left on stand-by ready for the next engagement.

The BWRO-CCD unit described herein was commissioned some two years ago and since operated none stop with feed water pumped from a shallow well (15 m deep) in Kibuz REIM some 30 miles west of the city of Beer Sheba in Israel. The source was formerly characterized with maximum TDS of 5250 ppm, corresponding to ≈7500 μS cm^{-1}, during the dry summer season with decreased salinity down to ≈6000 μS cm^{-1} during the rainy winter season. This source comprises a mixture of Brackish Water with clear domestic and industrial effluents originating from city of Beer Sheba and near by region. The 8ME4 BWRO-CCD unit under review was designed to met the indicated source variability of 6000–7500 μS cm^{-1} by operating in the respective recovery range 80–75% with maximum applied pressure around 21 bar (300 psi). In practice, the source salinity was found to climb up to 8800 μS cm^{-1} during mid summer days, at which point the allowed recovery of the unit was confined to 72% by the maximum pressure requirement of 21 bar.

The 8ME4 BWRO-CCD unit under review is housed in a 24 ft container with view displayed in Fig. 2. The fully automated unit was operated either directly from its control board or by remote control via a cellular modem. Remote control covered all essential functions of the unit and allowed real time follow up of all monitored parameters as well as excess to their history. The results reported herein for the 80% recovery of the 6800 μS cm^{-1} feed source were obtained under operational mode of fixed permeate flow and variable pressure with the following SP: 25 m^3 h^{-1} permeate flow (=HP); 26 m^3 h^{-1} concentrate recycling flow (=CP); 33 mS cm^{-1} high conductivity, or its maximum pressure equivalent of 21.5 bar, which triggers the engagement of the side conduit with the principle closed circuit whereby brine is replaced by fresh feed without stopping desalination; 32 mS cm^{-1} low conductivity, or its volume equivalent of 1000 l of brine replaced by fresh feed inside the closed circuit, which triggers the disengagement of the side conduit from the principle closed circuit without stopping desalination. Typical CCD results of the unit under review presented herein are of a 50 min interval at noon time of February 21st, 2011 with feed of 6800 ± 100 μS cm^{-1} at temperature of 22°C. Monitored cumulative volumes over 24 h of permeate (588 m^3) and Brine (144 m^3) revealed a desalination recovery of 80% with an overall energy consumption of 482 kWh manifesting specific energy consumption of 0.82 kWh m^{-3} with power consumption distribution furnished in Table 1. The maximum salinity (34.5 ± 0.2 mS cm^{-1}) of brine replaced with fresh feed (6.8 ± 0.1 mS cm^{-1}) inside the closed also manifests desalination recovery of 80% recovery.

Fig. 2. Front (left) and rear (right) views of the BWRO-CCD 8ME4 unit.

CCD is a batch process performed under variable pressure conditions with the same predetermined fixed flow rate of pressurized feed and permeate and a desired flow rate of recycled concentrate which is made continuous by the periodic replacement of brine inside the closed circuit by fresh feed without stopping desalination. The aforementioned requirements of a consecutive sequential CCD process are exemplified by online data of the 8ME4 Unit from February 21st, 2011 at noon with feed of 6800 mS cm^{-1} which was collected every minute. The sequential pressure variations on time evident in Fig. 3 where in sequence duration is 9.0 min with pressure variability range of 10–22 bar (average: 17.7 bar) and pressure difference between modules inlets and outlets of 0.72 ± 0.06 bar displayed in Fig. 4. The flow rate of pressurized feed displayed in Fig. 5 (average: 24.43 m^3 h^{-1}) and of permeate displayed in Fig. 6 (average: 24.35 m^3 h^{-1}) appear essentially identical in accordance with the CCD process requirement, and the actual experimental values deviate by a rather small margin from the flow SP of operation of 25 m^3 h^{-1}. The spikes in Figs. 4–6 appear to be associated with the low pressure range of sequences, and most probably reflect slow *vdf* response to fast variations in salinity when brine replaced by fresh feed inside the closed circuit.

Table 1
Energy consumption of 8ME4 REIM-I Unit with feed conductivity of 6800 mS/cm and system recovery of 80%

Pump	m^3/h	bar	% Eff	kW	%-hour	Effective Data	
						kW	kWh/m^3
HP[1]	24.4	15.57	60	17.59	100	17.59	0.72
CP	24.9	0.72	45	1.11	100	1.11	0.05
BRP[2]	60.0	0.70	40	2.92	12	0.35	0.01
Air compressor[3]				2.00	15	0.30	0.01
Miscellaneous[4]				1.00	100	1.00	0.04
						20.35	0.83

[1]The listed pressure is the difference between inlet and outlet of pump.
[2]The pump was operated 6.7 times per hour, each time for 1.1 min.
[3]The compressor operated 15% of the time with power supply of 2.0 kW.
[4]Anti-Scalant pump, Control board, Lights, with AC unit turned off.

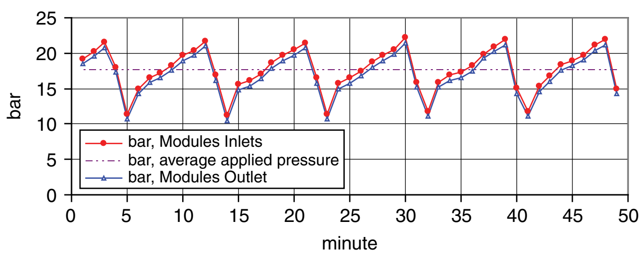

Fig. 3. Pressure variations on time.

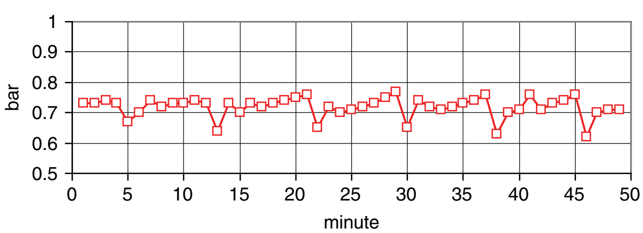

Fig. 4. Modules pressure difference on time.

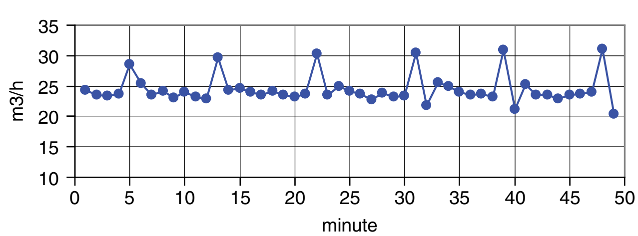

Fig. 5. Pressurized feed flow on time.

The illustrated fixed permeate flow desalination under variable pressure conditions implies operation with fixed Net Driving Pressure by complete analogy with conventional techniques.

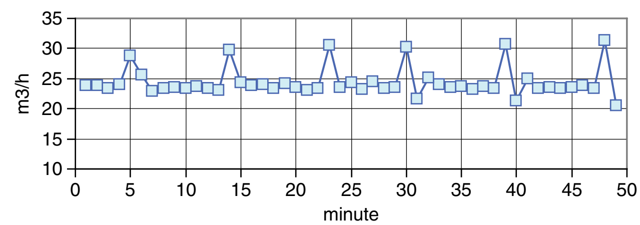

Fig. 6. Permeate flow on time.

The exemplified data of the new BWRO-CCD Technology is noteworthy also with respect to modules and membrane control. Since flow rates of HP and CP are selected as operational SP and in light of the close resemblance demonstrated between selected SP and the actual flow rates of operation, the new CCD technology enables extensive and flexible performance control of modules and membranes, not possible by any of the conventional techniques. For instance, the exemplified unit performance under review was dictated by the flow rates SP of 25 $m^3 h^{-1}$ for permeate (=HP) and 26 $m^3 h^{-1}$ for recycled concentrate (=CP) which implied the respective flow rates of 51 $m^3 h^{-1}$ and 26 $m^3 h^{-1}$ at inlets and outlet of modules, permeate flow rate of 25 $m^3 h^{-1}$, cross flow rate over membrane surfaces of 26 $m^3 h^{-1}$, mean flux of 19.3 lmh, percent Module Recovery (MR) per cycle of 49.0% (25/51 × 100), and estimated head element recovery also know as Maximum Element Recovery (MER) of 14.97%. The online monitored flow rates of HP, CP and HP + CP (module inlets) of the exemplified system under review displayed in Fig. 7 reveal close proximity between SP and actual results as well as between the desired and actual performance characteristics of the modules and elements displayed in Fig. 8. In the system under review the average flux is determined by the selected flow rate SP of HP; whereas, both MR and MER by the former SP as well as

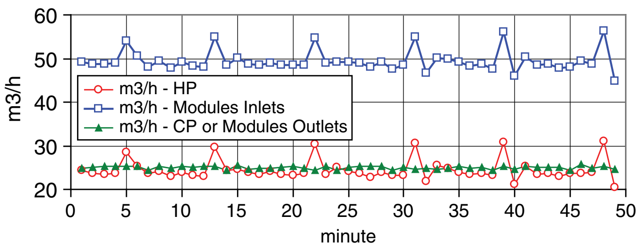

Fig. 7. Modules inlet and outlet flow rates on time.

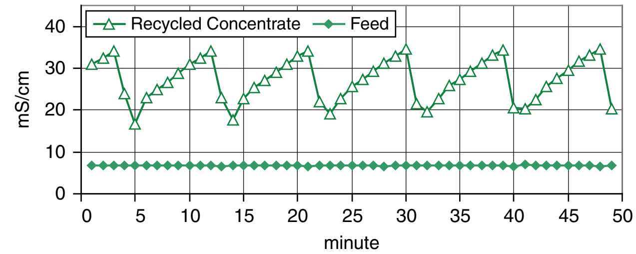

Fig. 9. Recycled concentrate and feed conductivity on time.

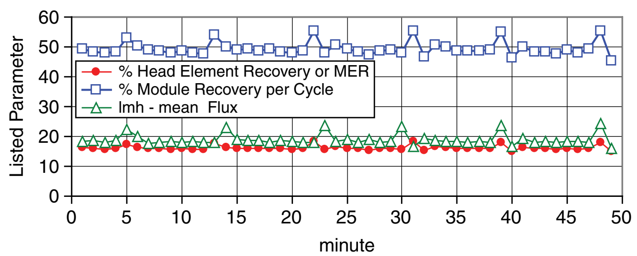

Fig. 8. Modules and membranes performance on time.

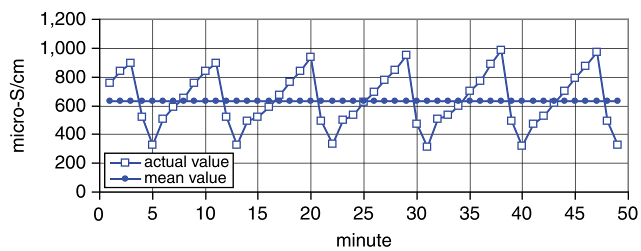

Fig. 10. Permeate conductivity variations on time.

by the selected flow rate set SP of CP. In simple terms, the change of average flux achieved by increased or decreased of the operational SP of HP; whereas, changes of MR and MER at a given flux achieved independently by increased or decreased of the operational SP of CP. Contrary to conventional techniques, the selected operational parameters of flux, MR and MER are independent of the system recovery which depends only on the SP dictating the maximum salinity of the recycled concentrate before being replaced by fresh feed through the engagement of the side conduit, and this SP may manifest either the EC or the applied pressure at which the desired said high salinity is attained. The use of short modules of four elements which eliminate the undesirable effects of the tail elements in conventional modules, combined with complete control of flux, MR, MER and system recovery by simple SP manipulation on the control board, either directly or through cellular remote control means, provide an enormous operational flexibility of online control unmatched by any existing RO technique.

The exemplified unit performance under review with respect to consecutive sequential salinity variations are manifested in Fig. 9 in reference to the solution conductivity of fed and recycled concentrate and in Fig. 10 in reference to the actual and mean conductivity of the produced permeates. The consecutive sequential nature of the new process dictates the increased salinity of the recycled concentrate and likewise the salinity of the produced permeate with maximum salinity of both dictated by the system recovery—higher system recovery implies higher maximum salinity of both recycled concentrates and permeates and vice versa. Attainment of 80% system recovery in the exemplified operation under the specified conditions of flux, MR and MER revealed fixed feed conductivity (6800 µS cm^{-1}), variable recycled concentrate conductivity in the range of 16–35 mS cm^{-1} and variable permeate conductivity in the range of 300–1000 µS cm^{-1} (mean: 630 µS cm^{-1}). The expected quality of permeates without changing the system recovery should be inversely proportional to the flux, or to the flow rate of HP; and therefore, increased flow rate of HP should yield better quality permeate and shorter sequential periods and vice versa. The large sequential variations of recycled concentrate salinity encountered in the system under review are expected to minimize bio-fouling factors, since bacteria growth is not favor under frequent and large concentration variations.

The exemplified 8ME4 BWRO-CCD REIM Unit was designed for automated operation in the feed salinity range 4000–5250 ppm (6000–7500 µS cm^{-1}) in the respective system recovery range 80–75%, and this meant system recovery inversely proportion to feed salinity in the indicated boundaries without need of operational SP changes. In practice, the observed feed range conductivity of 6000–8800 µS cm^{-1} manifested the system recovery range of 70–80% without need for SP changes.

The 8ME4 BWRO-CCD REIM Unit was also operated briefly over a period two days period using a low salinity feed of 4000 ± 100 µS cm^{-1} (4.0 ± 0.1 mS cm^{-1}) created by the blending of the REIM source with the so-called SAFDAN source of clear domestic effluents for agricultural irrigation with the salinity manifested by conductivity level of 1300 ± 50 µS cm^{-1} (1.30 ± 0.05 mS cm^{-1}). The SAFDAN source which originates in the populated

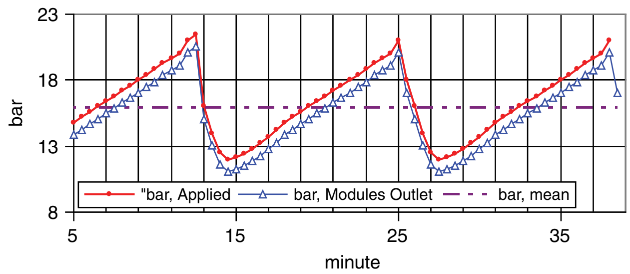

Fig. 11. Pressure variations on time.

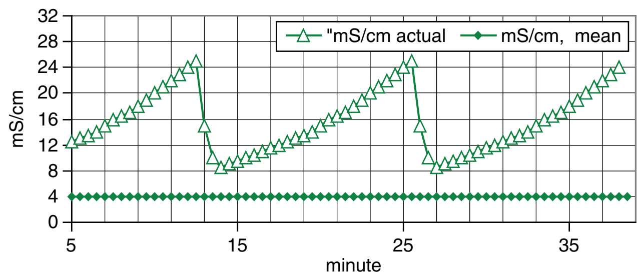

Fig. 12. Recycled concentrate and feed conductivity on time.

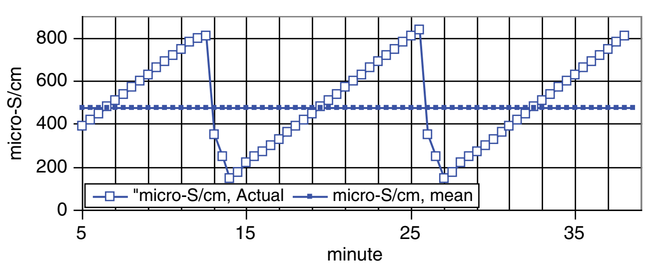

Fig. 13. Permeate conductivity variations on time.

central part of Israel is extensively used for irrigation in the southern part of the country. The desalination of the REIM-SAFDAN feed of 4.0 mS cm^{-1} with the 8ME4 REIM Unit was performed with SP as followed: 35 m^3 h^{-1} of fixed permeate flow; 36 m^3 h^{-1} of fixed concentrate recycling; 24 mS cm^{-1} recycled concentrate high conductivity for triggering conduit engagement, and 12 mS cm^{-1} recycled concentrate low conductivity for triggering conduit disengagement. The trial run of this REIM-SAFDAN feed source with pH of 7.2 was conducted at temperature of 22 ± 1°C. The aforementioned flow rates of operation imply MR = 49.3%, MER = 15.0% and average flux of 27 lmh. Results showing the characteristics consecutive sequential variations on time of pressure, recycled concentrate conductivity and permeate conductivity during this trial run are displayed the respective Figs. 11–13. The average sequence duration of the trial under review according to data in Figs. 11–13 is about 12.7 min during which period some 7.4 m^3 permeate produced and 1.0 m^3 brine removed manifesting RO system recovery of ≈88% [7.4 / (7.4 + 1.0) × 100], a value fully supported by the salinity of the feed and of the final salinity of the recycled concentrate when replaced by fresh feed in the closed circuit at the end of each sequence. The mean specific energy during this REIM-SAFDAN trial was of 0.82 ± 0.02 kWh m^{-3} with breakdown specified in Table 2 wherein the principle contributor is the HP with an average pressure output 16.1 bar and an input pressure of 2.0 bar, thereby amounting to an average effective applied pressure of 14.1 bar.

Conclusions

The BWRO-CCD 8ME4 REIM-I unit exemplifies a new CCD technology of conduits and valves which operates on the basis of hydrostatic principles, instead of the hydrodynamic principles of conventional BWRO

Table 2
Energy consumption of 8ME4 REIM-I Unit with feed conductivity of 4000 mS/cm and system recovery of 88%

Pump	m^3/h	bar	% Eff	kW	%-hour	Effective Data	
						kW	kWh/m^3
HP[1]	34.8	14.10	55	24.78	100	24.78	0.71
CP	36.0	0.92	45	2.04	100	2.04	0.06
BRP[2]	60.0	0.70	40	2.92	9	0.26	0.01
Air compressor[3]				2.00	10	0.20	0.01
Miscellaneous[4]				1.00	100	1.00	0.03
						28.29	0.81

[1]The listed pressure is the difference between inlet and outlet of pump.
[2]The pump was operated 4.7 times per hour, each time for 1.1 min.
[3]The compressor operated 15% of the time with power supply of 2.0 kW.
[4]Anti-Scalant pump, Control board, Lights, with AC unit turned off.

techniques, and allows high recovery with low energy. The low energy demand of CCD arises from the exact power supplied to the system continuously during the fixed flow variable pressure operation, the mixing effect of recycled concentrate with fresh feed at inlet to modules, and the unique procedure whereby brine in the closed circuit is replacement by fresh feed without stopping desalination through a side-conduit with a *negligible waste of Energy*. The energy saving benefits of CCD over conventional BWRO techniques expected on the basis of theoretical considerations are fully supported by the experimental data furnished hereinabove with respect to BWRO-CCD and elsewhere with respect to SWRO-CCD [e.g., 1.90 kWh/m^3 reported[5-6] for Mediterranean Water (4.1%) desalination with 47% recovery at flux of 13 lmh compared with lowest reported value of 2.67 kWh/m^3 for advanced conventional large plant under the same flux conditions].

The new consecutive sequential BWRO-CCD technology, exemplified with the REIM-I unit, is a genuine closed circuit desalination technique with brine occasionally removed without interruption of the closed circuit mode of operation. The benefits of this technology are as followed:

- A technology of simple design made of common parts and components.
- A technology of modular design for any desired production scale.
- A technology for very high recovery without the mandatory staging of conventional techniques.
- A technology of very low energy consumption with CCD of same flow rates of pressurized feed and permeate experienced continuously essentially without any energy loss due to brine disposal.
- A technology of highly versatility suitable for fixed or variable salinity feed sources and for maximum recovery made possible the constituents of the source.
- A technology with simple control of flux, module recovery, head element recovery and cross flow for any desired system recovery made possible by the salinity and the constituents of the source.
- A technology of low fouling (bio and particulate matter) due to use of short modules (3-4 elements each) which eliminate tail elements effects of conventional techniques; large salinity variations of recycled concentrate, fast cross flow over membranes surfaces, and frequent replacement of the entire brine in the system with fresh feed.
- A technology of high automation for remote control operation with minimum need for maintenance on location – demonstrated already by REIM-I unit over the past 27 months.
- A technology of infinite selections of operational parameters to suit the exact requirements of any specific Brackish Water Source.

The new BWRO-CCD proprietary[4] technology applies for diverse applications, small to large scale, some of which are listed below:

- Upgrade of existing water supply lines at the source or elsewhere along the line, intended for improved quality of supplies for domestic and/or industrial and/or agricultural applications. This approach may involve partial source desalination with high recovery and blend of permeate with the rest of the source according to the desired supply quality.
- Decontamination of ground and/or under ground water sources by partial or complete desalination of the source with high recovery and low energy. Exemplified already by nitrate content reduction (87 → 26 ppm) of a domestic supply line with up to 90% RO recovery and 94% of source recovery.
- Brackish Water desalination, including very high salinity sources, with low energy and maximum system recovery allowed by the source constituents in the presence of suitable anti-scale agents.
- Desalination of clear domestic effluents to so-called "Newater" permeates, to supplement potable water supplies as in Singapore or for quality upgrade of such a water source when used for irrigation as is practiced on a large scale in the State of Israel.
- Desalting of water received from cooling towers, softening of water supplies to a desired level, quality water supplies for industry, treatment of industrial effluent, and other related applications.

References

[1] R.I. Bratt, "Method and apparatus for fluid treatment by reverse osmosis", US Patent No 4,814,086.

[2] L. Szucs, K. Jozzsef and A. Szucs, "Method and apparatus for treating fluids containing foreign materials by membrane filter equipment", US Patent No 4,983,301.

[3] A. Efraty, "Variable Pressure Closed Circuit Desalination", PCT International Publication No WO O3/013704 A2 (20.02.2003).

[4] A. Efraty, "Apparatus for continuous closed circuit desalination under variable pressure with a single container", US Patent No 7,628,921 and related patents issued worldwide.

[5] A. Efraty, R.N. Barak and Z. Gal, Closed circuit desalination— a new low energy high recovery technology without energy recovery, D&WT, 31 (2011) 95–101.

[6] A. Efraty, R.N. Barak and 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, D&WT in press (2011).

[7] A. Hermoni, "Actual Energy Consumption and Water Cost for the SWRO Systems at Palmachim—Case History", IDA conference, November 2–3, 2010, CA, US.

[8] B. Liberman, "Presence and Future: Energy Efficiency Seawater Desalination", IDA conference, November 2–3, 2010, CA, US.

[9] R.C. Stover and M.A. Sanz, "Low Energy Consumption in the Perth Seawater Desalination Plant", IDA conference, October 21–26, 2007, Gran Canaria, Spain.

[10] F.H. Kiang, "Energy Efficiency Considerations of the Sing-Spring SWRO Plant, Tuas, Singapore", IDA conference, November 2–3, 2010, CA, US.