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Closed circuit desalination — A new low energy high recovery technology without energy recovery

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ABSTRACT

Closed circuit desalination of Mediterranean water with 47.5±1.5% recovery was demonstrated in the RO energy range 1.85–2.25 kWh/m³ for the respective flux range 6–18 lmh with head element recovery of 7.0±0.5%.

Keywords: Closed circuit desalination; Seawater, Low energy; High recovery; No energy recover

1. Introduction

Since the inception of RO application for desalination in the late fifties of the last century by Loeb and Sourirajan [1], this technique remained essentially unchanged over the past 50 years, despite of great improvements of membranes and energy recovery means. Conventional RO involves a hydrodynamic "plug flow" process with pressurized feed (Q_f) at inlet of modules containing semi-permeable membranes splits at outlet into two streams, one of pressurized brine (Q_b) and the other of none pressurized permeate (Q_p). Recovery (R_{ec}) in conventional RO [Eq. (1)] is a function of the number of membranes in line through which feed passes with limitations imposed by the feed flow and recovery associated with the head element. Flow balance of conventional RO [Eq. (2)] requires continuous release of pressurized brine (Q_b), and in order to make such a process energetically effective the power stored in Q_b needs to be recovered.

$$R_{ec}(\%) = \left(Q_p / Q_f\right) \times 100 \qquad (1)$$

$$Q_f = Q_p + Q_b \qquad (2)$$

In contrast with widespread conventional RO, the terms closed circuit desalination (CCD) or closed loop desalination originated in the patent literature [2–4] for a rare class of batch RO processes of little if any commercial prospects until recently. The typical apparatus for batch CCD displayed in Fig. 1 comprises a pressure vessel with one or more membrane elements inside, a feed pressurizing pump (HP), a circulation pump (CP) for concentrate recycling from outlet to inlet of module(s) as well as for pressure loss compensation (Δp), and a 3-way valve to enable brine replacement with fresh feed when batch desalination completed at a desired recovery level. Batch CCD operates on the basis of hydrostatic principles with same flow rates of pressurized feed and permeate. The cross flow over membranes is created in CCD by circulation means, instead of the excess feed flow requirement of conventional RO. Batch CCD takes place only in the presence of concentrate recycling, without which desalination stops due to immediate rise in concentration polarization. Batch CCD operates without need for energy recovery since the compression and decompression of the batch reactor during the respective steps of actuation and terminations involve the loss of negligible amounts of hydrostatic energy.

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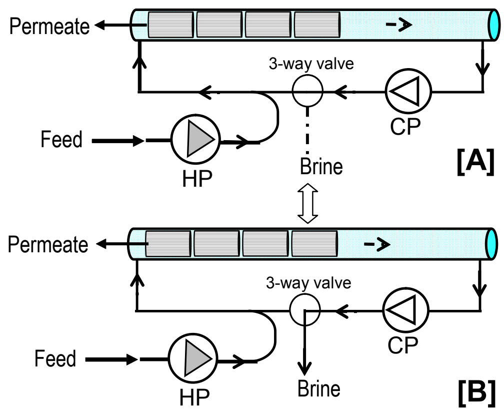

Fig. 1. [A] Batch CCD; [B] Batch reactor recharge without desalination.

Batch CCD operates by different rules compared with conventional RO with recovery ($R_{EC\text{-}CCD}$) expressed by Eq. (3), wherein V stands for the fixed intrinsic volume of the batch reactor and v for the permeate volume produced, or the feed volume consumed, during a single batch operation. If batch CCD performed with fixed feed flow (Q_f) under variable pressure conditions with mean pressure expressed by p, the volume term v expressed by Eq. (4), wherein T stands for a single sequence duration. Substituting v in Eq. (3) by Eq. (4) provides the relationship expressed in Eq. (5) between $R_{EC\text{-}CCD}$, T, V and Q_f (= Q_p). The module recovery (MR) of the unit displayed in Fig. 1, expressed by Eq. (6), is fully controlled from the flow rates of HP (Q_f) and CP (QCP). The specific energy (SP) terms of a batch CCD process are expressed by Eq. (7) and Eq. (8) for HP and CP, respectively, with total RO energy demand expressed by the sum of those two terms, wherein eff_{HP} and eff_{CP} stand for the efficiency factors of the respective pumps.

$$R_{EC\text{-}CCD}(\%) = \left[v/(v+V)\right] \times 100 \tag{3}$$

$$v = Q_f \cdot T = Q_p \times T \quad \text{since } Q_f = Q_p \tag{4}$$

$$\begin{aligned} T &= R_{EC} \cdot V / \left[Q_f \cdot (100 - R_{EC})\right] \\ &= R_{EC} \cdot V / \left[Q_p \cdot (100 - R_{EC})\right] \end{aligned} \tag{5}$$

$$MR(\%) = Q_f \cdot 100 / \left(Q_f + Q_{CP}\right) = Q_p \cdot 100 / \left(Q_p + Q_{CP}\right) \tag{6}$$

$$SE_{HP} = p / 36 / eff_{HP} \tag{7}$$

$$SE_{CP} = Q_{CP} \cdot \Delta p / 36 / eff_{CP} / Q_p \tag{8}$$

In contrast with conventional RO wherein recovery is a function of the number of membrane elements in line, recovery in batch CCD is only a function of the batch duration T, irrespective of the number of elements per module. The high energy efficiency of the batch CCD process manifests the gradual increase in pressure as function of increased system recovery [Eq. (3)] and a unique flow balance without pressurized brine rejection. Batch CCD requires smaller pressurizing means compared with conventional RO, since $Q_f = Q_p$ in the absence of pressurized flow of brine.

Incorporation of the enormous benefits offered by batch CCD in a continuous RO process was made possible by development of the consecutive sequential CCD technology for continuous desalination with [5] or without [6] side conduits, with the former technique suitable in particular for seawater desalination (henceforth, SWRO-CCD) and the latter for brackish water desalination (henceforth, BWRO-CCD) for domestic use and industrial applications. The BWRO-CCD technology unit design is essentially that of the batch reactor displayed in Fig. 1 with modifications to enable a two-step consecutive sequential desalination process with CCD of 100% recovery experienced most of the time (85%–90%) and with plug flow desalination (PFD) of 40%–50% recovery experienced part of time (10%–15%) for brine replacement with fresh feed (henceforth, BR or brine rejection). The CCD step in the process takes place with fixed flow of HP and CP under variable pressure conditions and the BR step initiated at a desired maximum applied pressure or maximum electric conductivity of the recycled brine. Termination of BR concomitant with resumption of CCD takes place in this process by volumetric means, when recharge of entire fixed volume of the closed circuit completed. The BWRO-CCD technology was demonstrated successfully during the past 18 months [7] by commercial units of 40 m^3/h permeate production capacity, operated with recovery of up to 93.5% with a feed source of 600 ppm TDS, 90% with a feed source of 2,500 ppm TDS and 87% with a feed source of 5,700 ppm TDS. The BWRO-CCD technology allows high recovery without staging with low energy demand in units of low installation and maintenance costs.

The schematic design of a consecutive sequential CCD unit for seawater displayed in Fig. 2 comprises a pressure vessel with one or more membrane elements inside; a feed pressurizing pump (HP), a circulation pump (CP) for concentrate recycling from outlet to inlet of module as well as for pressure difference (Δp) compensation; a side conduit (SC) of the same volume as the principle closed circuit (CC), valves and conduits means to enable engagement and disengagement between the CC and SC, and a low pressure (1–2 bar) brine replacement pump (BRP) for recharge of the SC with fresh feed. The principle operational positions of the system depicted in Fig. 2 are as follows: [A] CCD experienced in the CC with disengaged SC on stand-by with pressurized fresh feed; [B] CCD experienced in the expanded system of CC

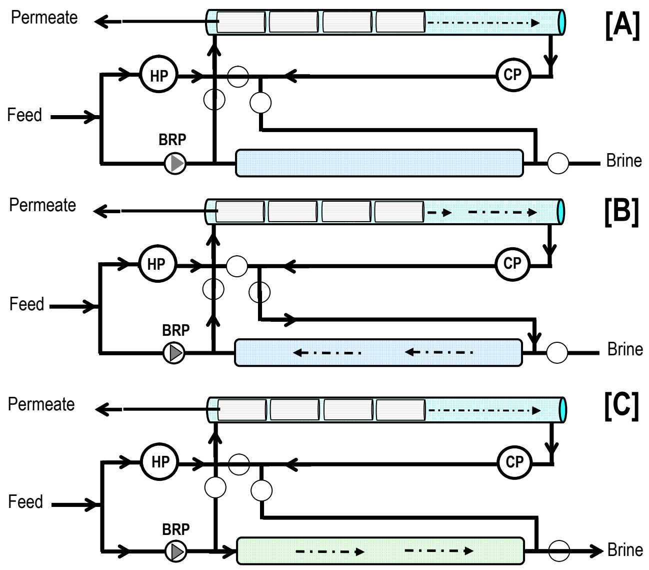

Fig. 2. [A] CCD with SC on stand-by for engagement; [B] CCD with SC engaged; [C] CCD with SC disengaged decompressed and recharged with fresh feed.

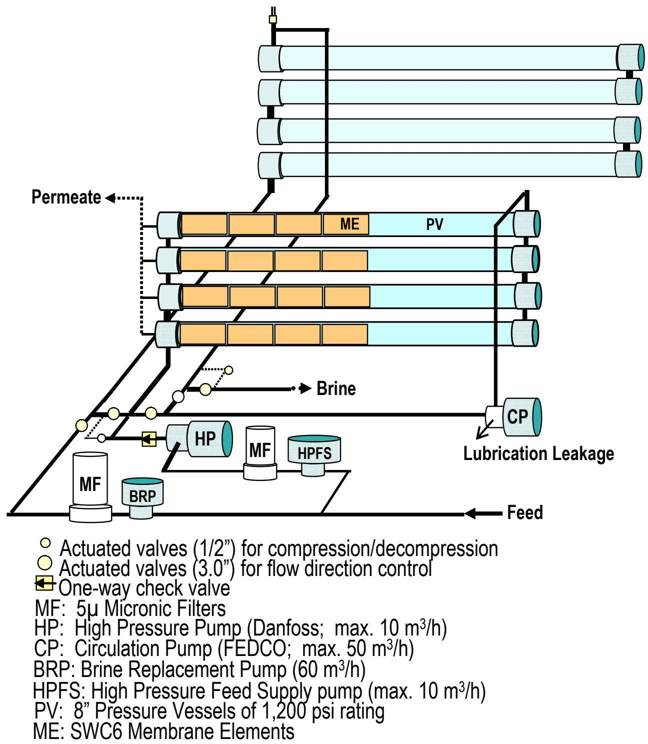

Fig. 3. Schematic design of the SWRO-CCD unit for the Mediterranean desalination trials reported herein.

and SC with fresh feed received in the former and brine collected in the latter while desalination continued; and [C] CCD experienced in the CC with disengaged decompressed SC recharged with fresh feed by the BRP, then sealed, compressed and left on stand-by as in Fig. 2A for next engagement displayed.

The entire consecutive sequential SWRO-CCD process performed with fixed flow rates of HP and CP under variable pressure conditions with engagement of SC initiated at a desired maximum applied pressure, and with disengagement determined volumetrically when the recharge of the entire closed circuit volume of the apparatus with fresh feed completed.

The new SWRO-CCD technology was ascertained by trials on Mediterranean seawater feed (4.1%) using the unit of the design displayed schematically in Fig. 3 with four modules of four elements each (henceforth ME4 module configuration). The continuously monitored data included flow and 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. The lubrication leakage of CP was determined from the flow rates difference of feed and permeate as well as by direct measurements, and the results presented herein are for zero leakage operation of CP. The performance characteristics of the SWRO-CCD unit described herein for the first time compare well with those of the similar BWRO-CCD units [7].

2. Summary of SWRO-CCD trials results and projections

Desalination of Mediterranean feed (average salinity of 4.1% and temperature range of 22–23°C) with 47.5±1.5% recovery (7.0±0.5% head element recovery) using the SWRO-CCD unit displayed in Fig. 3 (4 modules of 4 elements each) gave the RO energy range 1.85–2.25 kWh/m^3 in the respective flux range 6–18 lmh (Fig. 4) with mean efficiency (Fig. 5) of 82.6% for HP and 29.3% for CP and without need for energy recovery. The RO energy range 1.65–1.87 kWh/m^3 (Fig. 6) for the same feed under the same desalination conditions is attainable by the SWRO-CCD technology if efficiency of HP and CP increased to 88% (instead of 82.6%) and 60% (instead of 28.3%), respectively. Ocean water (3.5%) SWRO-CCD with the improved efficiency pumps is expected to proceed with RO energy in the range 1.5–1.7 kWh/m^3 (Fig. 7). Other noteworthy information concerning the SWRO-CCD trials includes the flow conditions (Fig. 8); the pressure conditions (Fig. 9); the consecutive sequential time intervals (Fig. 10); the performance of membranes (Fig. 11); the electric conductivity of permeates and brine (Fig. 12); and percent recovery (Fig. 13).

3. RO energy comparison between SWRO-CCD and conventional SWRO

Meaningful energy comparison between RO techniques should pertain to similar feed source salinity, flux and recovery. Practical experience gained by operating

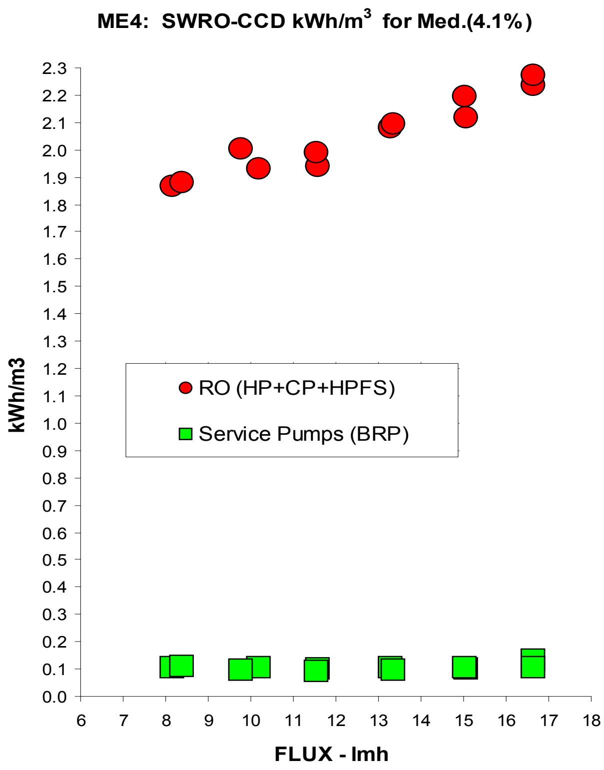

Fig. 4. Trials energies vs. flux.

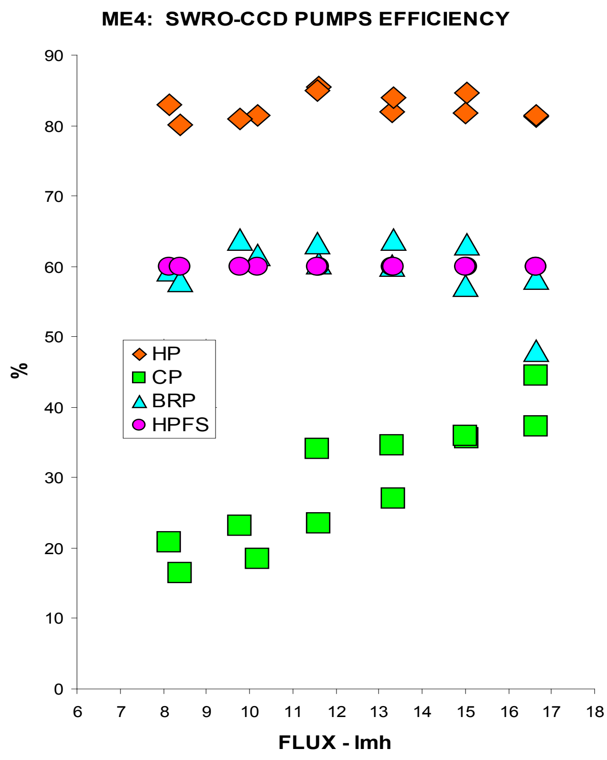

Fig. 5. Efficiency (*Eff*) of pumps vs. flux.

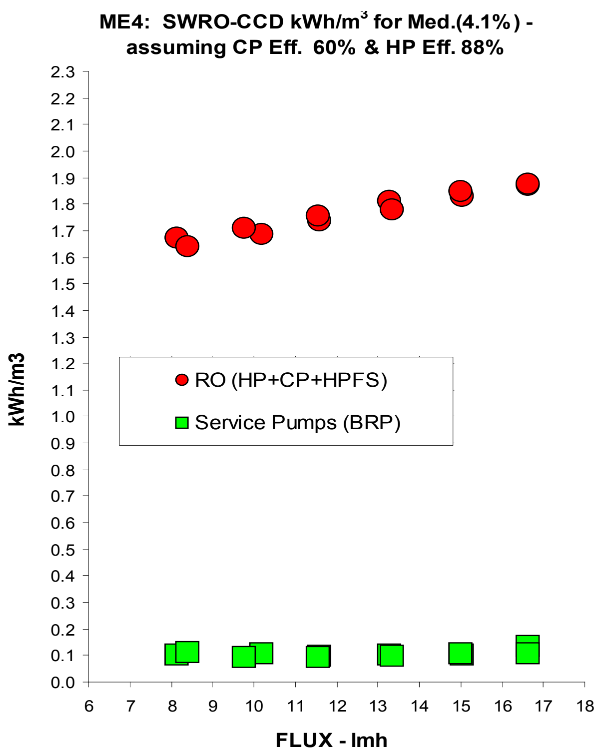

Fig. 6. Med. (4.1%) energy if pumps *Eff* improved.

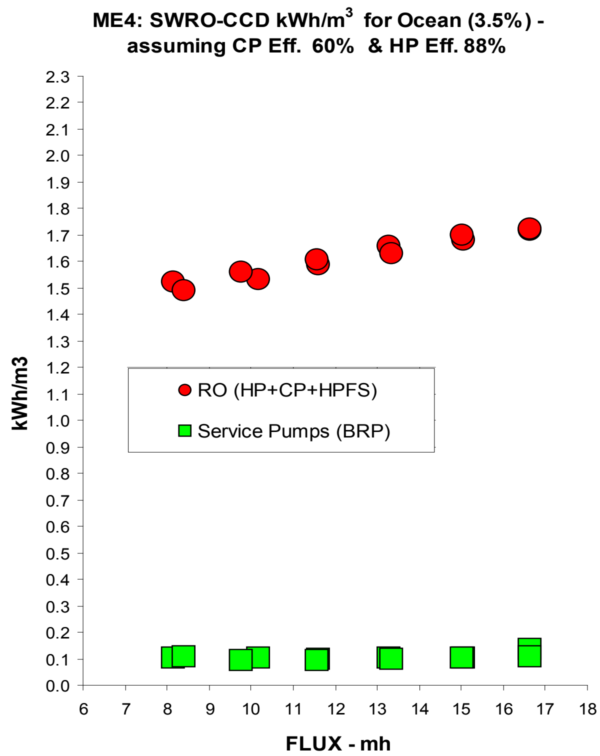

Fig. 7. Ocean (3.5%) energy if pumps *Eff* improved.

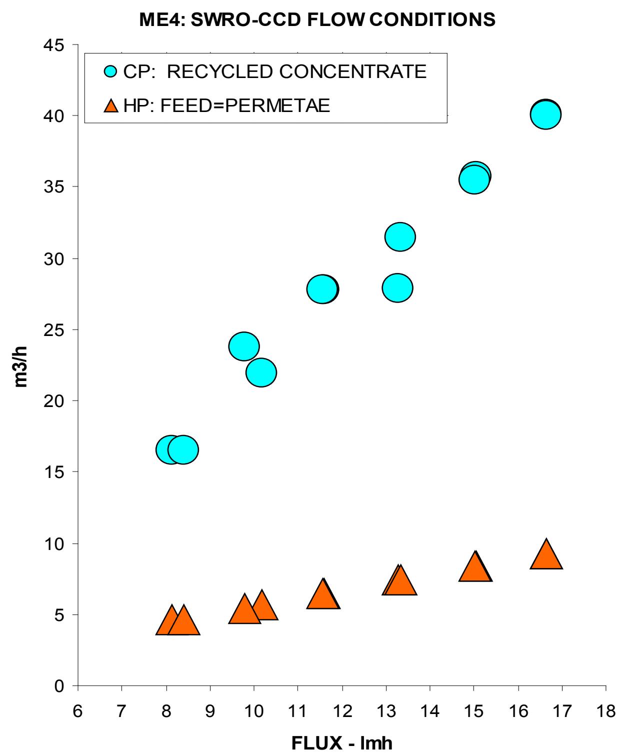

Fig. 8. Trials flow conditions.

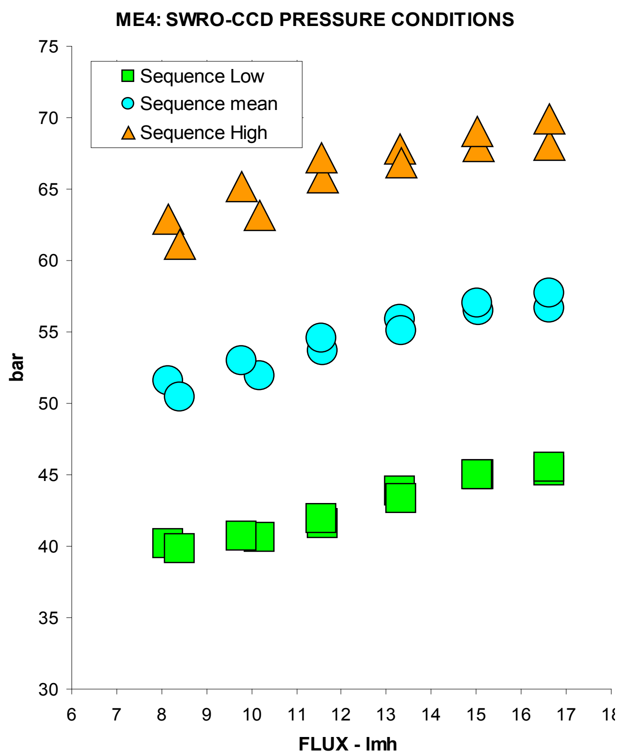

Fig. 9. Trials pressure conditions.

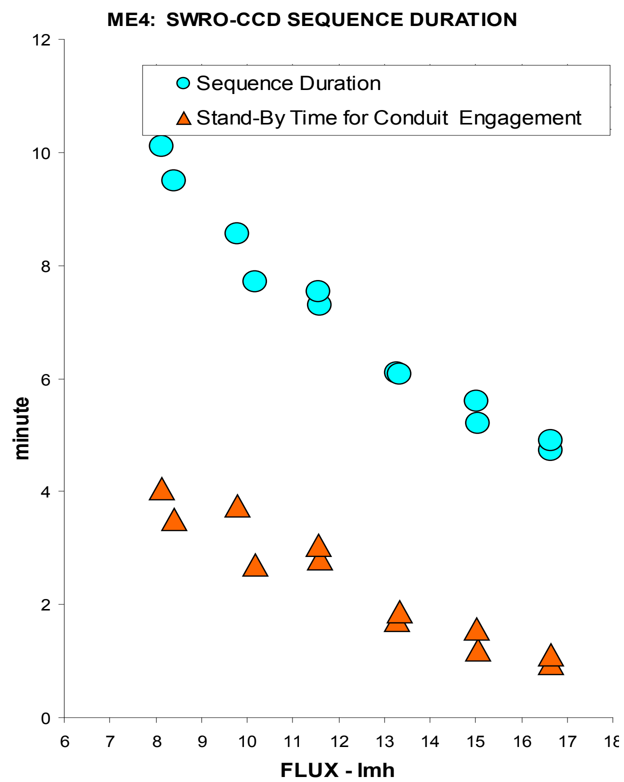

Fig. 10. Trials sequential durations.

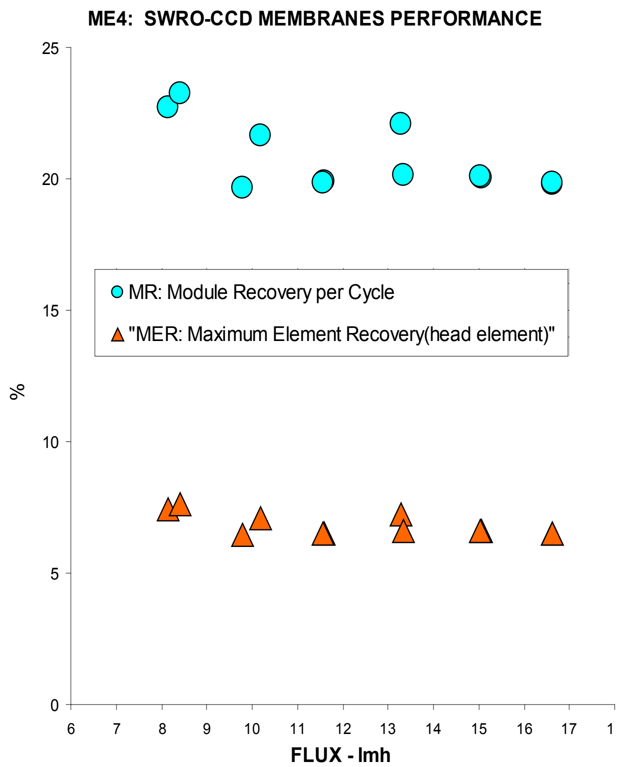

Fig. 11. Trials performance of membranes.

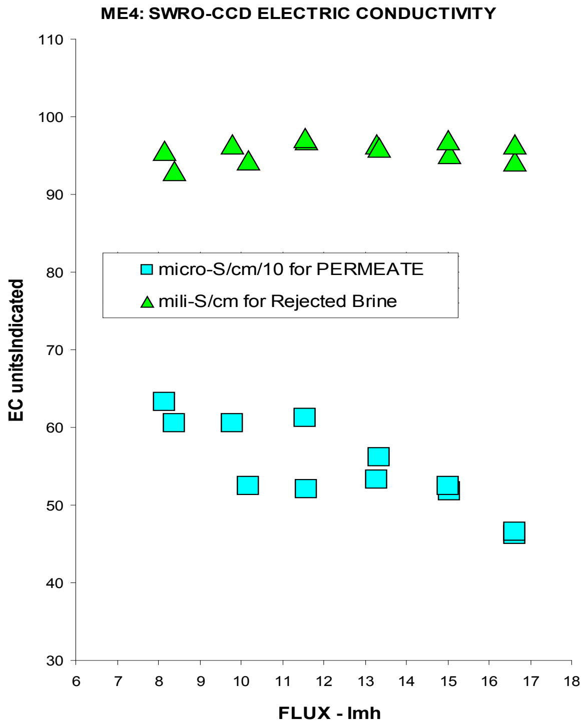

Fig. 12. Trials electric conductivity data.

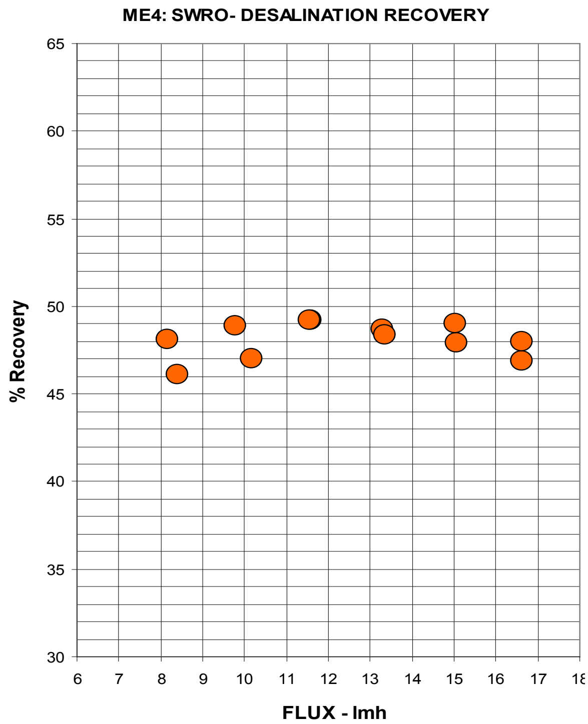

Fig. 13. Trials recoveries.

large conventional SWRO plants in Israel and elsewhere with average flux of 13–14 lmh and recovery of 46±2% revealed RO energies as follows (feed salinity in brackets): 2.73 kWh/m^3 for SWRO-PX in Hedera,Israel (40,000 ppm) [8]; 2.47 kWh/m^3 for SWRO-PX in Perth,Australia (34,000 ppm) [9]; 2.98 kWh/m^3 for SWRO-DWEER in Ashkelon,Israel (40,500 ppm) [10]; 3.64 kWh/m^3 for SWRO-DWEER in Tuas, Singapore (max. 35,000 ppm) [11]; 2.65 kWh/m^3 projected for SWRO-DWEER in Soreq, Israel (40,000 ppm) [7]; and 2.95 kWh/m^3 for SWRO-Pelton in Palmachim, Israel (max. 42,000 ppm) or 2.68 kWh/m^3 for the expanded Palmachim plant when operated by means of the Pelton-PX hybrid system [12]. The lowest RO energy of conventional SWRO according to the aforementioned is that of the SWRO-PX technique with consistent results reported for Hedera, Israel and Perth, Australia if account taken for feed salinity difference. The RO energy projected for the currently constructed Soreq, Israel SWRO-DWEER plant is well below the value experienced already in the Ashkelon, Israel SWRO-DWEER plant with the same feed salinity. Operated with the same Mediterranean feed under similar flux and recovery conditions of the large conventional SWRO plants in Israel, the measured RO energy (2.10 kWh/m^3 at 13.4 lmh) of the small experimental SWRO-CCD unit (4 modules of 4 membrane elements each) implies energy saving of 28.8% compared with the SWRO-Pelton plant in Phalmachim, 29.5% compared with the SWRO-DWEER plant in Ashkelon and 23.1% compared with the SWRO-PX plant in Hedera. RO energy savings by the SWRO-CCD unit of improved pumps efficiency (1.80 kWh/m^3 at 13.4 lmh — Fig. 6) of 39.0%, 39.5% and 34.1% are expected compared with reported data for respective SWRO-Pelton, SWRO-DWEER and SWRO-PX desalination plants in Israel. Noteworthy is that the new SWRO-CCD technology allows high recovery operation at higher flux with a small added energy increment and without exceeding the preferred test conditions specifications of membrane elements by their manufacturers.

4. Technology type

SWRO-CCD is a new technology of conduits and valves which departs from the principles of conventional RO and circumvents entirely the need for energy recovery (ER). Brine release by the SWRO-CCD technology takes place through side conduits under hydrostatic pressure conditions with a *negligible waste of energy*. ER means such as PX and/or DWEER apply only for conventional RO but not for SWRO-CCD due to the absence of pressurized brine flow. Evidently, the PX and DWEER devices are essentially feed pressurizing pumps powered by the pressurized brine flow of conventional RO; hence, such devices can not function in the absence of pressurized brine flow as in the case of SWRO-CCD. In contrast with conventional RO, the recycled concentrate flow in the

SWRO-CCD technology stores very little energy, since created by the CP at a small pressure difference (Δp < 1.0 bar).

5. Scope and prospects

The new SWRO-CCD technology is not confined to the flow, flux, recovery and pressure conditions of the trials described in present document. Evidently, many of the SWRO-CCD trials performed thus far confirmed the facile attainment of high desalination recovery (tried up to 53%) of Mediterranean feed with head element recovery maintained well under 10%, a feature impossible with conventional RO. Low recovery (e.g., 35%–38%) and flux (e.g., 7–8 lmh) SWRO-CCD trials of Mediterranean feed, performed with consecutive sequential pressure variations of 38.2–50.5 bar, revealed exceptionally low RO energy under 1.6 kWh/m^3, unattainable by conventional RO. High recovery (e.g., 48%–50%) and flux (e.g., 21–23 lmh) intended SWRO-CCD trials are expected to involve energy of 2.2–2.3 kWh/m^3 with head element recovery remained under 10%, features inaccessible by conventional RO. The SWRO-CCD technology also appears ideal for small compact RO units, since any desired recovery is attainable already at the level of a single element module unit with a desired performance over an extended flux range. The implication alternating side conduits in the context of the SWRO-CCD technology should enable the design of large production capacity units.

Experience gained thus far with the new SWRO-CCD and BWRO-CCD technologies [7] suggests the following major benefits:

- Major reduction of energy consumption (variable lower pressure instead of constant high pressure, and extremely low energy loss to the brine, with no need for any energy recovery devices).
- Feed water recovery not limited by design — each unit can reach the ultimate recovery made possible by a given water source, thereby, minimizing waste of source, pretreatment costs, and brine disposal expenses.
- Flexible operation with regard to pressure, flow, recovery and energy demand even with a variable salinity source.
- Reduced membrane fouling (both mechanical and biofouling); hence, less CIP cleaning expenses.
- Superior permeate quality (at any given recovery level due to prospects of high flux operation).
- Reduced installation costs (~30%) due to higher flux (less elements) smaller pressurizing pumps, absence of energy recovery means and simple designs without staging with common commercial components.
- Membrane performance without exceeding test conditions specifications declared by the manufactures even at high recovery and flux.
- Modular and scalable designs of high cost effectiveness for any production capacity, with simple and efficient monitoring and control systems.

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