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# 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

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ABSTRACT

Closed circuit desalination (CCD) trials of Mediterranean Water, performed with a new technology unit of different configurations comprising four modules each of 1–4 membrane elements, reveal 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 with efficiency of feed pressurizing and concentrate recycling means of 85% and 60%, respectively. The extensive experimental data of Mediterranean water desalination trials by the new technology disclosed herein, reveal an extraordinarily energy efficient technology of high flux capability which operates without any need for energy recovery.

*Keywords:* Closed circuit desalination; Sea water; High flux low energy; Reduced fouling; High recovery; No energy recovery

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 present report describes Mediterranean Water desalination trials using SWRO-CCD 4MEn apparatus of four different configurations ($n$ = 1–4), one of which (4ME4) is displayed schematically 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 (Danfoss – 10 $m^3$ $h^{-1}$), *HPB* for feed supply booster to high pressure pump (10 $m^3$ $h^{-1}$), *CP* for circulation pump (FEDCO, 50 $m^3$ $h^{-1}$), *BRP* for brine replacement pump (60 $m^3$ $h^{-1}$), *PV* for empty pressure vessels side conduit (8″–1200 psi rating),

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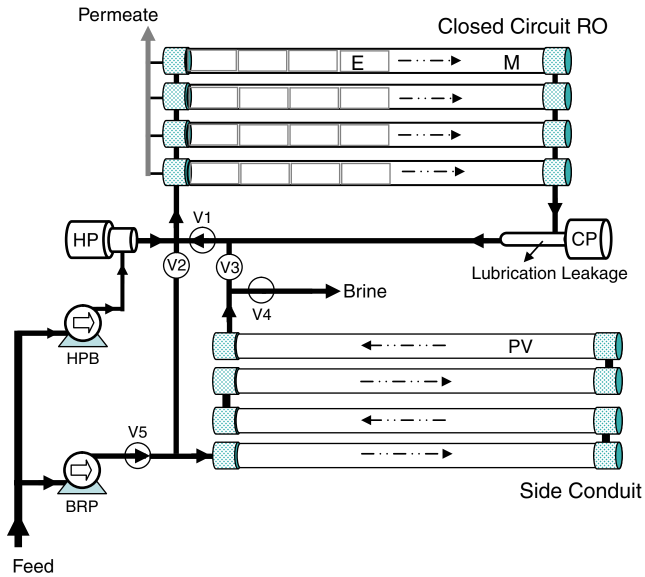


Fig. 1. The SWRO-CCD 4MEn apparatus with $n$ = 4 configuration.

*M* for modules (8″–1200 psi rating), *E* for SWC6 membrane elements and *V1–V5* for the principle actuated valves (3″) of the system. 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. The lubrication leakage of the 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. 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. SWRO-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 of actuated valves, a process whereby brine is replaced by fresh feed without stopping desalination. Initiation of engagement takes place at a selected maximum pressure set point (SP) which manifests the attainment of the desired system recovery by the principle closed circuit. Accordingly, higher maximum pressure 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.

Mediterranean Water (4.1%) desalination trials using the SWRO-CCD apparatus 4MEn with modules comprising 1–4 membrane elements ($n$ = 1–4) were performed under fixed flow conditions defined by the fixed flow rates of HP (range: 3–10 $m^3 h^{-1}$) and CP (range: 15–55 $m^3 h^{-1}$) as well as by defining the maximum operational pressure per sequence (range: 60–75 bar). The selected SPs of operational fixed flow during the CCD Mediterranean trials are displayed in Fig. 2 for pressurized feed ($Q_{HP} = Q_{PER}$) and recycled concentrate ($Q_{CP}$) for each of the apparatus configurations. The SP selection of fixed flow conditions per given trial dictates the membrane performance as manifested by module recovery (MR) per cycle and head element recovery (MER, maximum element recovery) for which data is provided in Fig. 3 as function of flux. The MR per cycle during the Mediterranean trials was selected according to module configuration as followed: 22 ± 2% (ME4); 19 ± 2% (ME3); 15 ± 1% (ME2); and 9 ± 3% (ME). The head element recovery (MER) during the Mediterranean trials was selected in the range of 6 ± 2% for the 4MEn ($n$ = 2–4) apparatus configurations and 9 ± 3% for the 4ME configuration.

Energy consumption during the CCD of Mediterranean Water was measured by accounting for the power meters of the pumps in the system. The efficiency of each of the pumps in the system was determined per each given trial from the available data of power, flow and pressure. The energy demand of the 4MEn ($n$ = 1–4) apparatus arises from the closed circuit RO system

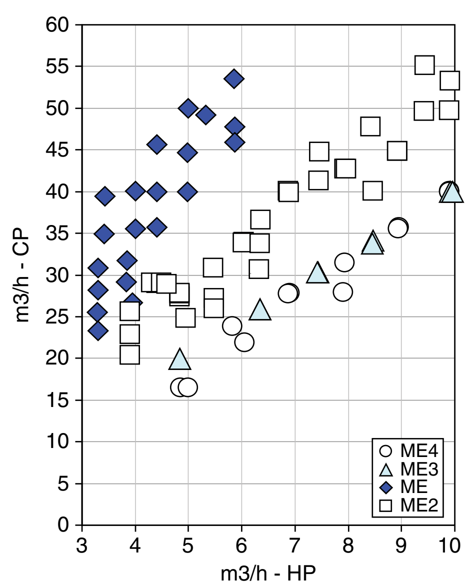


Fig. 2. Flow rates set points of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

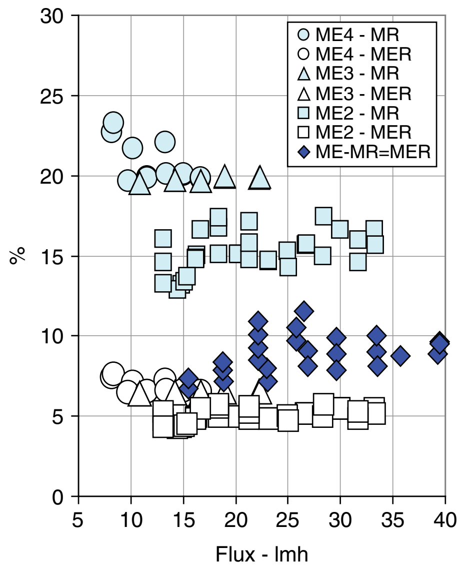


Fig. 3. MR and MER of 4MEn ($n$ = 1–4) versus flux during CCD of Mediterranean water.

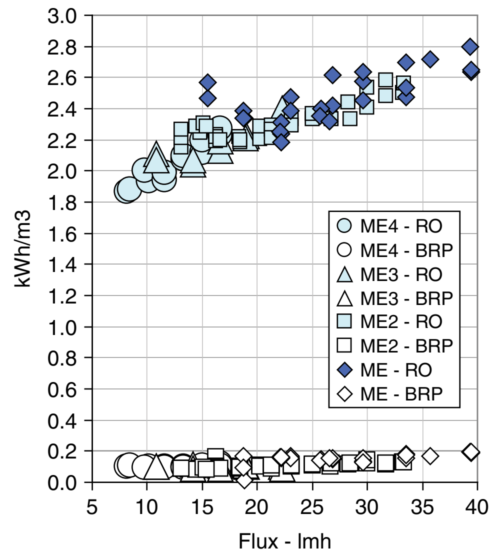


Fig. 4. Energy of RO (HP + HPB + CP) and BRP versus flux of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

(henceforth "RO energy") and from the pump used to replace brine by fresh feed in the disengaged decompressed side conduit (henceforth "BRP"). Most of the RO energy in the system under review originates from the high pressure pump (HP) with much lesser amounts contributed by the CP and the feed booster pump (HPB). While RO energy is continuously required, the BRP operates intermittently and its energy consumption depends on flow, pressure and duration of operation per sequence. Faster flow of BRP is concomitant with a shorter duration of brine replacement by fresh feed in the side conduit and vice versa. Accordingly, the energy consumption of the BRP is none related to the actual CCD process, but only to the speed with which the side conduit is being recharged—faster recharge requires more energy and vice versa. The specific RO energy and BRP energy are both expressed in kWh $m^{-3}$, and therefore, do account for permeate rate of production.

Experimental RO and BRP energies encountered during the CCD trials of Mediterranean Water with the 4MEn apparatus in its four configurations ($n$ = 1–4) are displayed in Fig. 4 as function of flux. The efficiencies of pumps during these experimental trials are revealed in Fig. 5 also as function of flux. Variations in the efficiencies of pumps, noticed in particular with respect to CP, are attributed primarily to the wide flow range of operation utilized during these trials which in most of case was outside the high efficiency range of the pumps. Fore instance, the CP centrifugal pump was operated during the trials in the flow range 15–55 $m^3$ $h^{-1}$ (Fig. 2), whereas, its efficient flow range is around 50 $m^3$ $h^{-1}$. Likewise, the positive displacement HP pump was operated in the flow range of 3–10 $m^3$ $h^{-1}$ part of which is well outside the recommended speed (rpm) range for high efficiency, although in this instance the encountered efficiency variations were not as pronounced as in the case of CP. The data furnished in Fig. 4 reveals near linear relationship of RO energy and flux (8–40 lmh) over a wide range, this despite the none ideal flow conditions of pumps with respect to efficiencies during most of the trials. In order to generate a uniformed correlation between RO energy and flux, all experimental RO

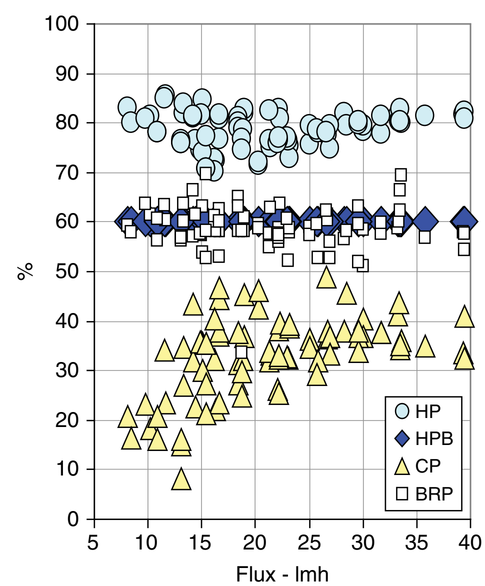


Fig. 5. Pumps efficiency versus flux of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

energies were extrapolated to HP and CP efficiencies of 85% and 60%, respectively, thereby eliminating the efficiency variability effects of these pumps, and the results of this treatment for the CCD of Mediterranean Water (4.1%) is displayed in Fig. 6. The analogous correlation of RO energy versus flux for Ocean Water (3.5%) displayed in Fig. 7 was generated on the basis of the data in Fig. 6 by accounting for difference in salinity between the sources (3.5% instead of 4.1%). The exceptionally low RO energies over a wide flux range displayed in

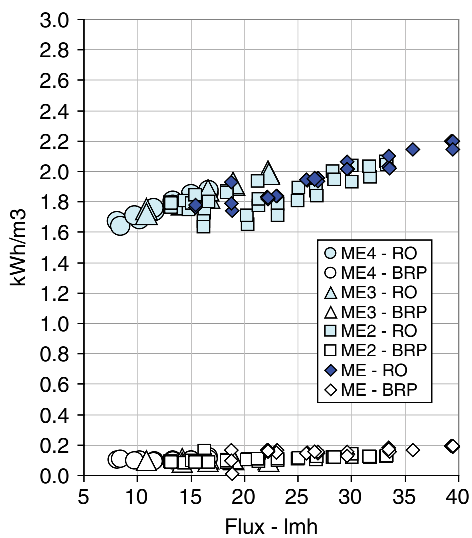


Fig. 6. RO energy (HP-85% + HPB + CP-60%) and BRP versus flux of 4MEn ($n$ = 1–4) extrapolated for CCD of Mediterranean water.

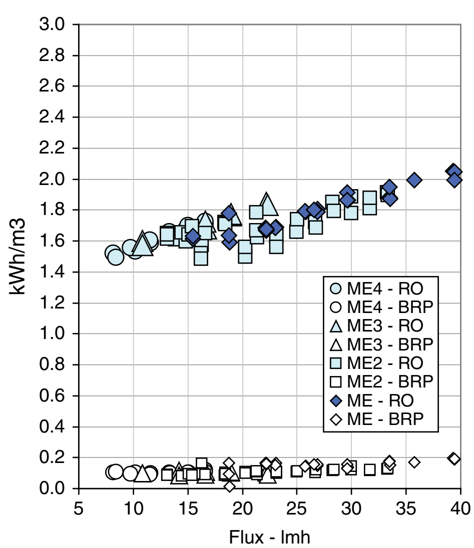


Fig. 7. RO energy (HP-85% + HPB + CP-60%) and BRP versus flux of 4MEn ($n$ = 1–4) extrapolated for CCD of ocean (3.5%) water.

Figs. 4, 6 and 7 were neither observed nor reported before for the desalination of Mediterranean Water and/or Ocean Water without use of Energy Recovery means and/or without exceeding Test Conditions specifications of membrane elements. Large conventional SWRO Plants for the desalination of Mediterranean Water utilize long modules of 7–8 membrane elements each as well as efficient Energy Recovery means and operate at an average flux of 13–14 lmh with head element recovery >12% and RO energy consumption >2.7 kWh $m^{-3}$. Compared with large conventional SWRO plants, Mediterranean trials of the small SWRO-CCD 4MEn apparatus with modules of three and four elements each ($n$ = 3–4) under average flux of 13–14 lmh with head element recovery of 6 ± 2% proceed with RO energy of 1.9–2.1 kWh $m^{-3}$ (Fig. 4), with prospects of a further drop in RO energy to 1.7–1.8 $kWm^{-3}$ (Fig. 6) made possible if pumps efficiency improved, and this without need of energy recovery. The different behaviors of conventional SWRO and SWRO-CCD with respect to RO energy, flux, energy recovery and head element recovery manifest unrelated RO methods of different prospects, the former which has already been developed to the state of the art level and the latter which is just emerging.

Maximum pressure SP during the consecutive sequential SWRO-CCD process manifests recycled concentrate salinity of the desired system recovery with higher pressure SP concomitant with increased system recovery and vice versa. The maximum pressure SP triggers the engagement of the side-conduit with the closed circuit RO whereby brine is replaced by fresh feed while desalination continues. After engagement completed, applied pressure continues to rise by 1–3 bare before starting to drop to a low level, characteristic of fresh feed desalination under the flow and flux conditions of the system. Accordingly, pressure variations encountered during a consecutive sequential CCD process of fixed flow take place between high and low with mean pressure being the sole expression which defines the specific energy of the high pressure pump (HP), since $Q_{HP} = Q_{PER}$. The maximum applied pressure conditions as function of flux applied during the CCD trials of Mediterranean Water displayed in Fig. 8, and the correlation between maximum applied pressure and system recovery displayed in Fig. 9, provide comparative data of said parameters (maximum pressure, flux and recovery) also in relationship to the configuration of the 4MEn Apparatus. In the maximum applied pressure range of 60–75 bar and flux range of 8–40 lmh, the system recovery range of the various 4ME4 configurations was found as followed: 46%–50% for $n$ = 3–4; 41%–50% for $n$ = 2; and 30%–46% for $n$ = 1. The ease of attainment of high recovery in the 4MEn system under review appears to be in the order $n = 4 > n = 3 > n = 2 > n = 1$.

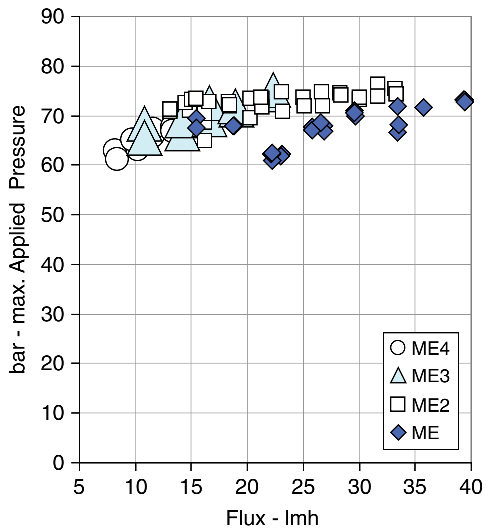


Fig. 8. Maximum applied pressure versus flux of 4xMEn ($n$ = 1–4) during CCD of Mediterranean water.

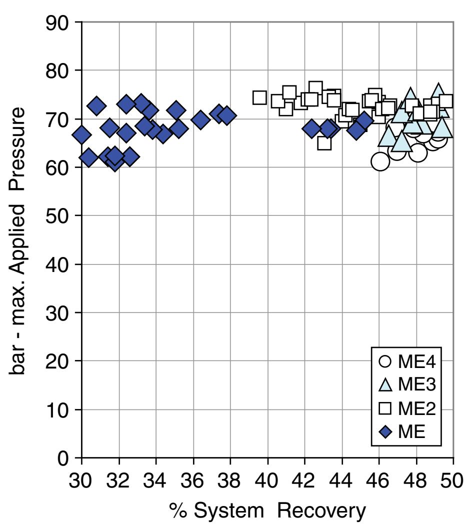


Fig. 9. Maximum applied pressure versus system recovery of MEn ($n$ = 1–4) during CCD of Mediterranean water.

The correlation of mean applied pressure and flux during the CCD trials of Mediterranean Water displayed in Fig. 10 reveals increased mean applied pressure concomitant with increased flux and vice versa. The mean applied pressure range and flux range for the various 4MEn configurations appears to increase in the order of $n = 4 > n = 3 > n = 2 > n = 1$. The correlation of RO energy and mean applied pressure during the CCD trials of Mediterranean Water displayed in Fig. 11 is noteworthy since the pressurizing pump (HP) is the principle contributor to RO energy in CCD processes and its contribution under fixed flow conditions relates only to the mean applied pressure because

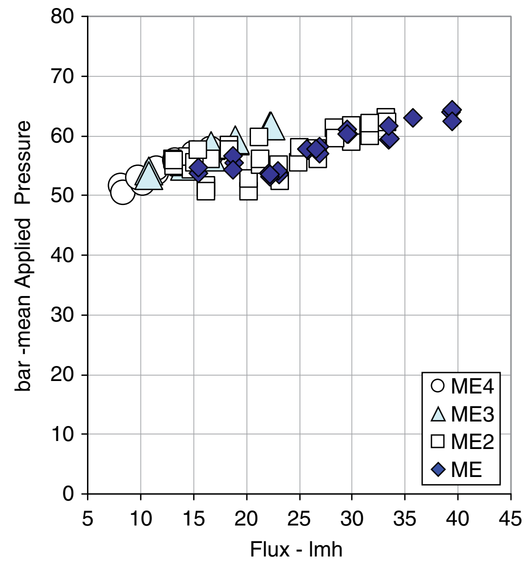


Fig. 10. Mean applied pressure versus flux of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

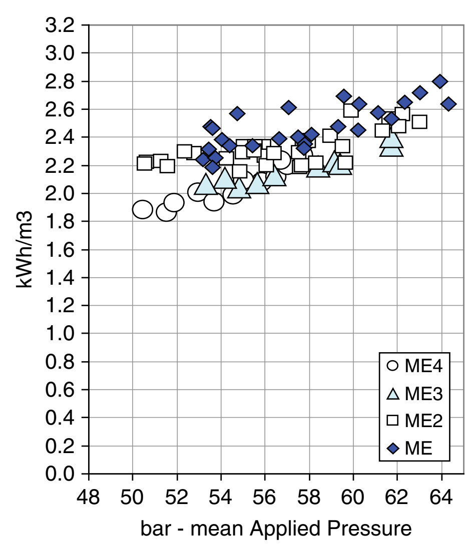


Fig. 11. RO energy versus mean applied pressure of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

$Q_{HP} = Q_{PERM}$. The approximate ranges of RO energy, flux and mean applied pressure in the various configurations of the 4MEn apparatus displayed in Figs. 10 and 11 are as followed: *4ME4*: 1.8–2.2 kWh $m^{-3}$, 8–16 lmh, 50–56 bar; *4ME3*: 2.0–2.3 kWh $m^{-3}$, 10–22 lmh, 52–61 bar; *4ME2*: 2.1–2.5 kWh $m^{-3}$, 13–35 lmh, 50–63 bar; and *4ME*: 2.2–2.8 kWh $m^{-3}$, 16–42 lmh, 53–64 bar. It should be pointed out that the upper flux ranges during the CCD trials of Mediterranean Water using the various configurations of 4MEn (n = 1–4) were confined by the maximum flow rate (≈10 $m^3$ $h^{-1}$) of the HP, and therefore, the upper RO energy ranges were confined as well in view to the dependence of RO energy on flux.

The correlation of maximum EC of recycled concentrates and flux during the CCD trials of Mediterranean Water with the 4MEn ($n$ = 1–4) apparatus displayed in Fig. 12, manifest the rejected brine concentration at the end of each of the consecutive sequences in the process. Accordingly, the maximum EC of recycled concentrates during the CCD Mediterranean trials should reveal a near linear relationship with the system recovery, as is displayed in Fig. 13, with higher maximum conductivity associated with higher system recovery and vice versa. The near linear relationship displayed in Fig. 13 arises from small variability in the ratio concentration/conductivity over the range covered by the rejected brine during the Mediterranean trials reported herein.

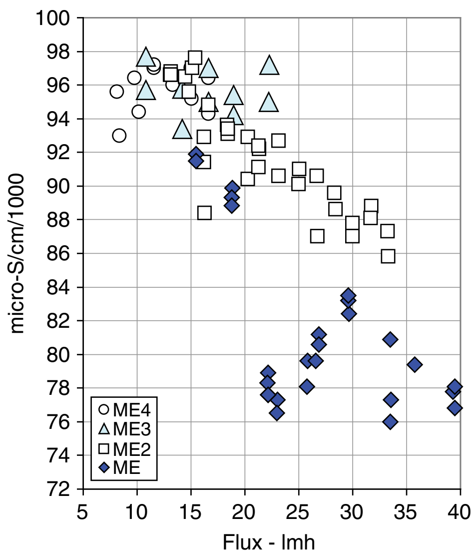


Fig. 12. Maximum electric conductivity of recycled concentrate versus flux of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

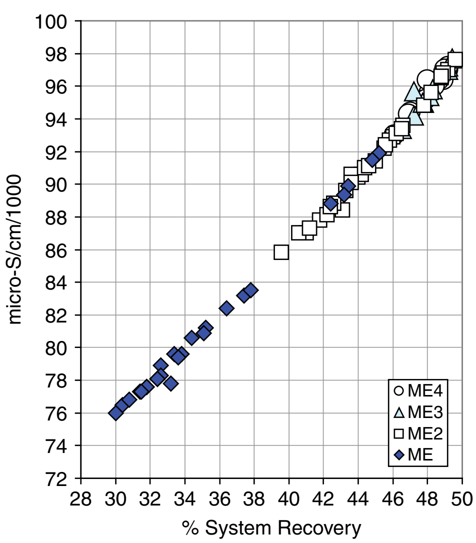


Fig. 13. Maximum electric conductivity of recycled concentrate versus recovery of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

Permeates quality received during CCD varies sequentially in light of its relationship to the recycled concentrate in the closed circuit, and therefore, the EC of permeates changes between low to high at start and end of each sequence, respectively. The conductivity data of permeates presented hereinafter stand for a mean sequential value. The mean EC of permeates received during the CCD trials of Mediterranean Water with the 4MEn apparatus as function of flux, displayed in Fig. 14, reveal improved permeates quality with increased flux for each of the configurations of the apparatus as would be expected by theory. Permeates quality in CCD process also depend on system recovery, since increased recovery implies increased salinity of recycled concentrate, and therefore of produced permeates as well. Increased mean EC of permeates with increased system recovery is evident from the data presented in Fig. 15.

The new CCD process is a consecutive sequential batch process with brine replacement by fresh feed occurring at the end of each sequence without stopping desalination. Under the fixed flow and variable pressure conditions experienced during the CCD trials with Mediterranean Water using the 4ME4 apparatus of fixed intrinsic volume, the sequence period is defined by the flux and the system recovery, with increased flux and lower system recovery concomitant with shorter sequence periods and vice versa. The selection of flux and system recovery in CCD should account for sufficient time to enable the disengaged side conduit to undergo brine replacement with fresh feed and then

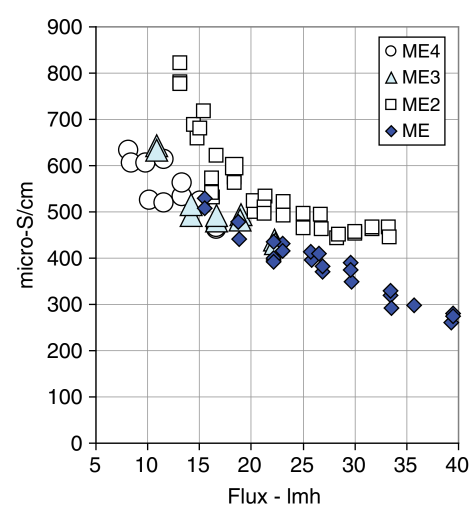


Fig. 14. Mean electric conductivity of permeate versus flux of 4MEn ($n$ = 1–4) during CCD of Mediterranean water.

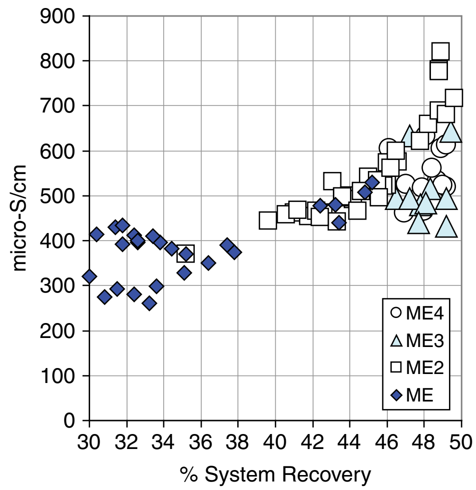


Fig. 15. Mean electric conductivity of permeate versus recovery of 4xMEn ($n$ = 1–4) during CCD of Mediterranean water.

remain compressed on stand-by for the next engagement. Accordingly, the control of sequence period is an essential requirement to enable an uninterrupted continuous CCD process. Sequence periods as function of flux during the CCD trials of Mediterranean Water are displayed in Fig. 16 for the system recoveries displayed in Fig. 9 as function of maximum applied pressure which is related to flux in Fig. 8. The selection of flux and system recovery in these trials was intended to allow a *minimum of 30 s stand-by period* before compressed side-conduit with fresh feed is made to engage with the principle RO closed circuit—the emphasis is on a minimum stand-by period since in most trials the selected conditions allowed much longer stand-by periods.

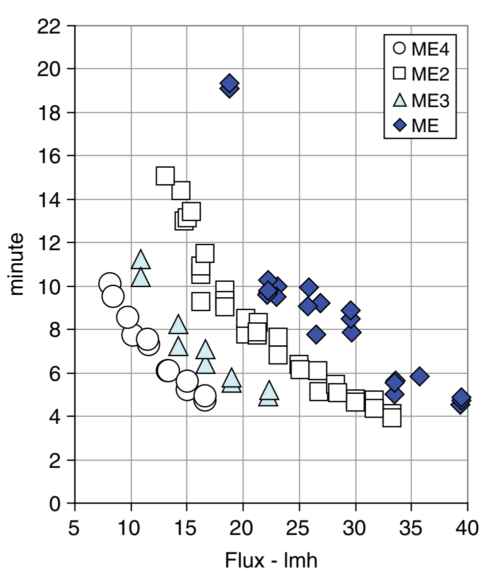


Fig. 16. Sequence period versus flux of 4xMEn ($n$ = 1–4) during CCD of Mediterranean water.

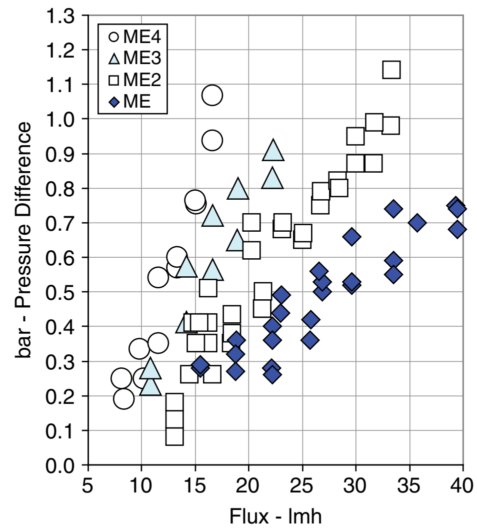


Fig. 17. Modules pressure difference versus flux of 4xMEn ($n$ = 1–4) during CCD of Mediterranean water.

Modules pressure difference ($\Delta p$) encountered during the fixed flow variable pressure CCD trials of Mediterranean Water, displayed in Fig. 17, show dependence on flux and on 4MEn ($n$ = 1–4) apparatus configuration. Translation of the maximum $\Delta p$ per configuration to average pressure drop per element reveals the following results: *4ME4* – 0.27 bar element$^{-1}$ at 16 lmh; *4ME3* – 0.31 bar element$^{-1}$ at 22 lmh; *4ME2* – 0.54 bar element$^{-1}$ at 34 lmh; and *4ME* – 0.79 bar element$^{-1}$ at 40 lmh. Accordingly, the maximum allowed $\Delta p$ value specified for the SWC6 membrane element of 10 psi (≈0.69 bar) was exceeded during the Mediterranean trial only with the 4MEn ($n$ = 1) apparatus configuration when operated with flux over 30 lmh. It should be pointed out that the principle configurations of the apparatus under review with 3 and 4 elements per modules have been shown to operate with relaxed $\Delta p$ even under flux conditions of 22 lmh which is well above the average flux of operation (13 lmh) of conventional SWRO plants.

## Conclusions

SWRO-CCD is a new technology of conduits and valves operated on the basis of hydrostatic principles instead of the hydrodynamic principles of conventional SWRO techniques. The exceptionally low RO energy consumption without need of energy recovery demonstrated during the CCD trials of Mediterranean Water manifests an inherent property of the CCD technology unmatched by any existing SWRO technique. The low energy demand of CCD arises from the exact power supply to the system during each stage of the variable pressure fixed flow process, the mixing effect of recycled concentrate with fresh feed at inlet to modules, and the unique procedure whereby brine is replacement by fresh feed in the closed circuit without stopping the desalination through a side-conduit under hydrostatic pressure conditions with a *negligible waste of energy*. In theory, no existing SWRO technology can match the energy performance of CCD even with the most sophisticated ER device. Accurate comparison between RO energy of CCD and SWRO should account for the same feed salinity, system recovery and membrane elements type, and such information is only partially available. Nonetheless, scarce information reported thus far on RO energy consumption of large conventional SWRO plants worldwide revealed a minimum 2.67 kWh $m^{-3}$ for Mediterranean [6,7] Sea Water desalination and a minimum 2.47 kWh $m^{-3}$ for Ocean [8,9] Sea Water desalination and this information should be compared with the relevant (13–14 lmh) CCD RO energies furnished in Figs. 4, 6 and 7.

Another noteworthy feature demonstrated during said CCD trials pertains to the wide flux range options of operation, unparallel by any existing technique, which implies a greater utility of existing membrane elements without exceeding their test conditions specifications. For instance most conventional SWRO plants operate with an average flux of 13 lmh, whereas the CCD Mediterranean trials reported herein reveal the prospects of much higher operation flux (e.g., 22 lmh) with the saving of ≈40% of the membrane elements and improved quality permeates.

In contrast with conventional SWRO, system recovery in CCD is defined only by the selected maximum applied pressure of operation, since membrane performance is independent of pressure and separately controlled from the selected fixed flow rates of HP and CP. For instance, 45%–50% system recovery during the Mediterranean trials with the 4MEn ($n$ = 2–4) apparatus was demonstrated with head element recovery under 8% irrespective of flux; whereas, the reaching of such recoveries at flux of 13–14 lmh with conventional SWRO techniques requires head element recovery of 12% and more. In simple terms, the head element performance in CCD takes place under exceptional mild conditions which are unattainable by conventional techniques. The short modules in the 4MEn ($n$ = 1–4) apparatus when operated with fixed flow and flux of choice should enable improved performance even compared with the front 1–4 elements of conventional SWRO modules of 7 or 8 elements, since the membrane performance is fully controlled independent of applied pressure.

In the CCD process, the rate flow of pressurized feed and permeate are the same and no other feed pressurizing means (e.g., PX or DWEER with their booster pumps for 2–3 bar pressure enhancement) are required. Accordingly, flow rate of permeate production ($Q$) by CCD also implies $Q$ flow rate of pressurizing means (40–70 bar) and approximately $2.4 \pm 0.4\ Q$ low pressure ($0.8 \pm 0.3$ bar) concentrate recycling means. Saving on pressurizing means as well as on membrane elements by the new CCD technology implies an apparatus with smaller pressurizing mean, lesser components of smaller design and operational complexity which translate to enhanced installation and operational cost effectiveness compared with conventional SWRO techniques.

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