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CCD Series No-11: single module compact SWRO-CCD units of low energy and high recovery for seawater desalination with solar panels and wind turbines

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ABSTRACT

The continuously flow-staged and pressure-boosted seawater reverse osmosis-closed circuit desalination technology of low energy, high recovery irrespective of the number of elements per module and wide flux range characteristics opened the door to the design of small compact single module units with two to four elements (8´´) for flexible permeate production of up to 100 m^3/d. The design features and performance characteristics of such compact MEn (n = 2–4) units are analyzed in the present paper by a theoretical model in terms of flow, flux, energy, power, recovery, permeate production, and quality as well as the time period of the consecutive sequential process. The theoretical model- simulated performance results with 32,000 ppm NaCl, equivalent to typical Ocean water of 35,000 ppm, are consistent with experimental results and reveal high recovery (50%) over a wide flux range (10–25 lmh) which extrapolate to the energy of 1.24 kWh/m^3 (85% *eff*. of HP and 75% *eff* of CP) and1.05 kWh/m^3 (100% *eff* of HP and 100% *eff* of CP) under near- zero flux conditions demonstrating performance at the theoretical minimum energy level unmatched by any conventional technique. The unique performance characteristics of the small compact units under review makes them ideal for marine applications (water supplies to cargo vessels and oil rigs) as well as for the entire water supplies of shore-line communities with population of up to 1,000 residents and the drinking and cooking water requirements of as many as 10,000 residents. Moreover, the wide range flux performance capability of said units make them ideal for integration with renewable energy sources through solar panels and/or small wind turbines for low- cost seawater desalination by means of free and clean renewable natural energy.

Keywords: CCD; SWRO; Compact RO units; High recovery; Low energy; Solar panels energy desalination; Wind turbines power desalination

1. Introduction

The era of seawater reverse osmosis (SWRO) desalination started with the pioneering work of Loeb and Sourirajan [1] in the early sixties of last century and since gained enormous momentum due to the increased depletion and/or deterioration of ground and underground water supply sources, combined with the growing demand for fresh water supplies by the rapidly expanding global population. Global climate changes as result of adverse environmental and ecological effects have also contributed to the development of fresh water shortages in various parts of the world and stimulated the application of the SWRO technology for fresh water supplies in many coastal regions worldwide. SWRO is an energy- intensive technology as revealed by the 2.5–3.5 kWh/m^3 reverse osmosis (RO) energy range reported for some large advanced desalination plants operated with Mediterranean (~40,000 ppm) [2–4] and Ocean (~35,000 ppm) [4,5] seawater feed. The total energy consumption by such plants, including pre- and post-treatment processes, is found in the range of 3–5 kWh/m^3 and manifest an average of 1.6 kg CO_2 emission per cubic meter produced permeate. In light of the growing costs of crude oil and since electric power generation from fossil fuels enhances the global "green-house effect" due to extensive emission of CO_2, emphasis in the development of advanced SWRO technologies is placed on low-energy RO processes with effective energy recovery (ER) means. A recent review article in Science entitled "The Future of Seawater Desalination: Energy, Technology, and the Environment" by Elimelech and Phillip [6] provides an excellent comprehensive survey of SWRO with emphasis on energy aspects and since, several more recent publications [7–9] described a new technology of seawater reverse osmosis desalination in closed circuit (SWRO-CCD), whereby near- absolute RO energy consumption was demonstrated without need of ER means. The CCD approach to RO has revealed exceptional performance benefits such as low energy consumption without need for ER, high recovery irrespective of the number of elements per pressure vessel, a wide range operational flux (8–38 lmh), low scaling and fouling (including bio-fouling) characteristics, and a flexible performance control of elements and modules unmatched by conventional RO techniques.

Recovery by conventional SWRO plug flow desalination proceeds as a function of the number of lined, tail to head, elements inside pressure vessels and attainment of higher recovery requires a longer line of elements. Accordingly, conventional SWRO requires long pressure vessels, each for seven to eight elements, to enable desalination recovery of 40–45% with head element recovery of 10% or of 45–50% with head element recovery of 12–14%. Apart from long modules, conventional SWRO also requires ER means to become energetically effective. The requirements of long modules and ER means make the design of compact small (<100 m^3/d) SWRO units a difficult task even if small diameter elements (2.5´´ and 4.0´´) are installed instead of standard size elements (8.0´´). Compact small SWRO units are extensively used for drinking water supplies in cargo ships, tankers, off-shore oil-rigs as well as in many shore-line communities worldwide where shallow shore wells of clean seawater are accessible for desalination without need of expensive pretreatment procedures. Small compact mobile SWRO units for drinking water supplies are also used by the military, although such units are intended for open-sea intake and require auxiliary filtration means. In many of the places where small compact SWRO units are required, grid electricity is either expensive or not available at all and this raised an interest to integrate such units with solar panels and/or small wind turbines for energy supply. The direct integration of small conventional SWRO units with natural energy sources of variable power output is non trivial in light of the limited flux flexibility of the conventional techniques—conventional SWRO techniques are designed for a narrow flux range operation and increased/decreased production can only take place through increased/decreased number of modules and not through large flux variations.

The present paper describes the design and projected performance characteristics of single module small compact SWRO-CCD units (≤100 m^3/d) comprising two to four standard elements (8´´) of high recovery and low energy consumption without ER of an extraordinarily large operational flux flexibility which makes them ideal for integration with solar panels and/or small wind turbines for low- cost desalination of seawater along shore lines worldwide.

2. Compact SWRO-CCD units of a single module ME2 configuration

The new CCD technology unit design displayed in Fig. 1 comprises a single pressure vessel with two conventional (8´´) elements for SWRO desalination and some empty space, a single feed supply pump, a single high-pressure (HP) pump equipped with a variable frequency drive (*vfd*), a single circulation pump (CP) equipped with a *vfd*, and a side-conduit (SC) of the same intrinsic volume as that of the closed circuit with valve means (small circles) to enable engagement/disengagement between the closed circuit and the SC for brine replacement by fresh feed at a desired recovery level with a negligible loss of energy. The design also contains monitoring means, such as flow monitoring means of recycled concentrate (FM_{RC}), HP feed (FM_f), SC feed (FM_{SC}), and permeate (FM_p); electric conductivity (EC) monitoring means of recycled concentrate (CM_{RC}), feed (CM_f), and permeate (CM_p), pressure monitoring means at module's inlet (PM_I) and outlet (PM_O), and feed temperature monitoring

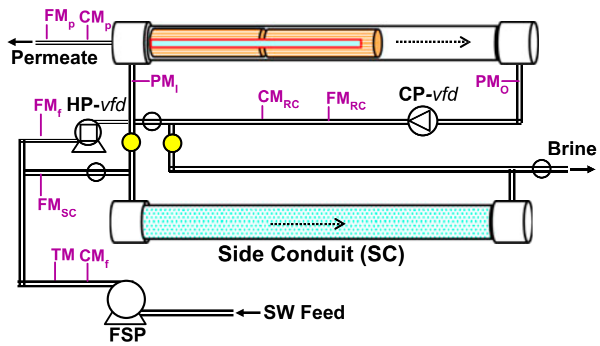

Fig. 1. A schematic design of a small SWRO-CCD unit with ME2 configuration comprising a single module of two elements (8´´).

means (TM). The configuration displayed in Fig. 1 describes a disengaged SC undergoing replacement of brine by fresh feed at near atmospheric pressure, while desalination is continued nonstop in the closed circuit; thereafter, the SC is sealed, compressed, and left on stand-by for the next engagement. The CCD unit under review in Fig. 1 operates with fixed feed/permeate flow ($Q_f = Q_p$) and cross- flow (Q_{CP}) under variable pressure conditions with flow rates selected by set-points and controlled by the flow monitoring means through the *vfd* devices of HP and CP. The selection of the pressurized feed flow (Q_f) and cross-flow (Q_{CP}) determines the module recovery $[(Q_f/(Q_f + Q_{CP}) \times 100]$; whereas, the desalination recovery is determined by the selected set-point of maximum applied pressure, or of maximum EC of recycled concentrate, which manifest the desired desalination recovery of the system. The operation of the unit is conditioned by concentrate recycling with CP which avoids adverse concentration polarization effects, compensates for the Δp drop and enables dilution of the recycled concentrate with fresh feed at module inlet. The stopping of CP immediately causes a sharp increase of pressure due to a rapid rise of concentration polarization.

The compacting of the design in Fig. 1 can be achieved by use of two single-element pressure vessels (8´´, ~130 cm long) and their stacking on top of each other in the closed circuit and the SC sections, and such a spread design is illustrated in Fig. 2(A) and a compact design in Fig. 2(B). In the figures under review, CCD takes place in the pressurized section (red), while the disengaged decompressed (blue) SC undergoes brine (green) replacement by fresh feed (pale blue) and thereafter, the SC is compressed and left on stand-by for the next engagement with the closed circuit. Compression and decompression of the SC take place under hydrostatic conditions at the expense of negligible loss of energy. The SWRO-CCD ME2 unit of the type displayed in Fig. 2(A) is intended for maximum desalination of 50 m^3/d of 50% recovery at flux of 25 lmh or for smaller production at lower flux. The flux and the recovery are independent of each other and determined by the selected set-points of operation which may be changed "on-line" without stopping the desalination. The estimated dimensions of the unit in Fig. 2(A) for 50 m^3/d or less depending on flux are 170 × 80 × 150 cm (length–width–height). Apart from standard size (8´´) pressure vessels and elements, the unit also contains a positive displacement HP pump of 2.2 m^3/h with flow rate maintained up to 80 bar (e.g. ***Danfoss*** APP-2.2–72 cm long and 30 cm maximum diameter); a CP pump with maximum flow rate of 8.2 m^3/h at Δp of 1.0 bar; and conducting lines of 2/3´´-2.0´´ diameters according to sections (see Fig. 2(A)) of flow speed under 2.5 m/s and valve means of 1.5´´ connections, of which three are common electrically actuated two-way valves and two are check valves. Components in contact with pressurized feed and/or brine are made of Super-Duplex for continuous use or from SS316L for occasional use, with pressure specification of 80 bar rating. The monitoring means and control board of the unit are required to satisfy a minimum configuration of operational set points (Q_f of HP-*vfd*; Q_{CP} of CP-*vfd*; FM_{CP}; $FM_{SC,}$ and PM_I) with additional features as deemed necessary.

The pressurized feed (2–4 bar) flow to the unit displayed in Fig. 2(A) originates from the shore well or open-sea intake pump and said flow should be sufficient to provide the needs of the HP and SC. A feature of the ME2 design not displayed in Fig. 2(A) is a small permeate container (~120 L) which enable complete flash of the ME2 membrane section when the unit is stopped.

3. Simulated performance of the compact SWRO-CCD ME2 unit

The simulated performance of the compact size ME2 unit displayed in Fig. 2(A) is exemplified in Table 1(A) at 25˚C and flux of 15 lmh for feed of 32,000 ppm NaCl (equivalent to Ocean seawater of 35,000 ppm) using common membrane elements such as SWC6-MAX or alike, and the information disclosed in this table is divided into columns labeled at the bottom 1–20. The top data in Table 1(B) pertains to basic information related to pressure vessels, elements, module type, and set-points of operation. In the example under review, the test-conditions data of the

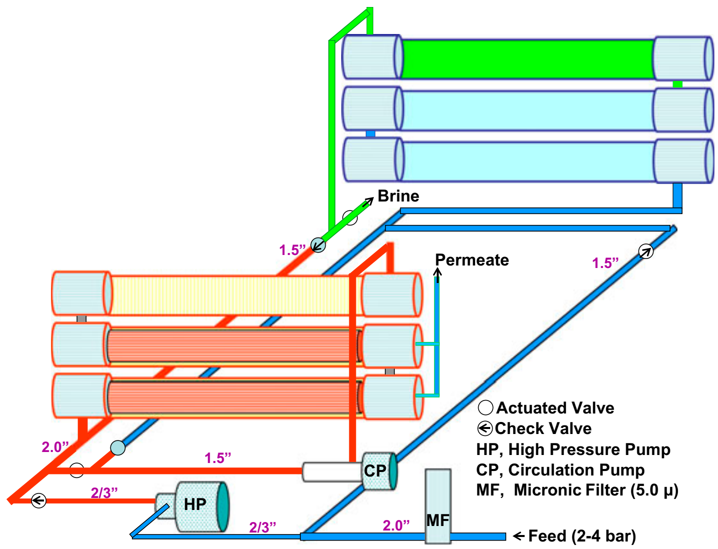

Fig. 2(A). A schematic illustration of a spread design of the SWRO-CCD ME2 unit configuration comprising a split single module of two elements (8´´) with free space and a SC of the same split pressure vessels configuration.

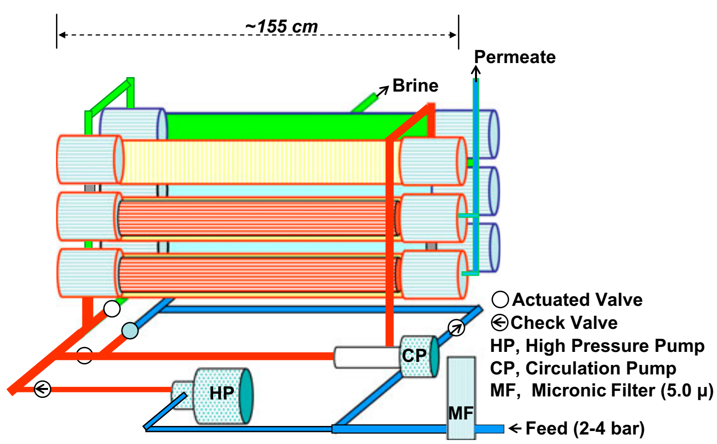

Fig. 2(B). A schematic illustration of the compact design of the SWRO-CCD ME2 unit configuration comprising a split single module of two elements (8´´) with free space and a SC of the same split pressure vessels configuration.

selected elements provide both A and B coefficients; the split module (8´´) design of ME2 corresponds to a combined pressure vessel length of 390 cm (3 × 130) with free closed circuit volume of 97.1 L assuming an element volume of 15 L. The cited operational conditions of fixed flux (15 lmh) and cross-flow (4.9 m^3/h) correspond to a module recovery (MR) of 25%, and the maximum applied pressure (60.8 bar) manifests a desalination recovery of 55.6%

The entire data in Table 1(A) is derived from theory using the basic information on top of the table and conventional expressions, including RO and power equations, and the explanations are provided hereinafter according to the labeled columns in the bottom of the table. The mode of the sequence is cited in column 1 and the CCD progression as function of the number of cycles is furnished in column 2. The module inlet and outlet concentrations (%) are outlined in columns 3 and 4, respectively, with module inlet concentration accounting for the dilution effect due to mixing of recycled concentrate with fresh feed. The cumulative sequential time (minute) of the CCD cycles is provided in column 5 on the basis of the fixed cycle period term (1.19 min/cycle) specified in the top of the table. The applied pressure (p_{appl} − bar) during CCD cycles in column 6 is derived by Eq. (1); wherein, μ stands for flux, A for permeability coefficient, T_{CF} for temperature correction factor, $\Delta\pi_{\text{av}}$ for

Table 1(A)
The simulated performance of the compact SWRO-CCD ME2 (E = SWC6-MAX-8´´) unit with feed of 32,000 ppm NaCl at fixed flux of 15 lmh, MR = 20% and 25˚C with up to 55.6% recovery

TEST - SWC6 MAX		UNIT DESIGN		CCD Parameters		Temperature					
40.8	m2/Element	1	Modules	3.20	% Initial feed	≥25	25	°C	≤25	25	°C
25	m3/day	2	Elements/Module	15.0	lmh Flux	≥25	1.000	TCF	≤25	1.000	TCF
32,000	ppm NaCl	390	cm long PV	1.22	m3/h Permeate (=Q_{HP})						
41	bar Applied Pressure	20	cm diameter PV	20	% Module Recovery	**C≥25°C**					
10	% Recovery	15	liter element volume	4.90	m^3/h Qcp	TCF=EXP[**2640**(1/298-1/(273+C)]					
25	Centig.	5	% lines volume			**C≤25°C**					
99.60	% Salt Rejection	97.1	liter per module	0.29	bar Δp	TCF=EXP[**3020**(1/298-1/(273+C)]					
15.08	bar NDP	97.1	liter per design	4.2	psi Δp						
25.53	l/m2/h Flux			1.19	min/cycle CCD	**Pumps**					
1.693	l/m2/h/bar -A			0.106	av-MR/Element-CCD	0.85	HP *eff*.				
0.080	l/m2/h - B			1.037	av-pf - CCD*	0.75	CP *eff*.				

π(bar)-C(%)					
32000	ppm NaCl Feed	25.60	bar Osmotic Pressure	8.00	π(bar)/C(%)

ME2 MODULE DATA				CCD Sequence Cycles							CCD Sequence Combned Data					PERMEATE			
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Power & Energy		REC	Cycle		mean	
Mode	Step	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	μS/cm
CCD	1	3.20	4.00	1.19	37.8	37.8	1.512	1.235	0.053	0.043	0.024	0.024	1.565	1.279	20.0	200	399	200	399
CCD	2	3.84	4.80	2.38	43.6	40.7	1.743	1.330	0.053	0.043	0.024	0.049	1.795	1.373	33.3	240	479	220	439
CCD	3	4.48	5.60	3.57	49.3	43.6	1.973	1.424	0.053	0.043	0.024	0.073	2.026	1.467	42.9	279	559	240	479
CCD	4	5.12	6.40	4.76	55.1	46.4	2.203	1.518	0.053	0.043	0.024	0.097	2.256	1.561	50.0	319	639	259	519
CCD	5	5.76	7.20	5.95	60.8	49.3	2.434	1.612	0.053	0.043	0.024	0.121	2.487	1.655	55.6	359	719	279	559
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

average concentrate-side osmotic pressure difference, Δp for module inlet–outlet pressure difference, p_p for released permeate pressure, and π_p for average permeate-side osmotic pressure.

The mean applied pressure in column 7 is the average applied pressure which also takes account of the preceding applied pressures of the sequence. The power (P, kW) demand of HP in column 8 is derived by Eq. (2); wherein, Q_f (m^3/h) stands for pressurized feed flow, p (bar) for applied pressure (p_{appl}), and *eff* for the efficiency factor of HP. The specific energy of HP (kWh/m^3) in column 9 is derived by Eq. (3); wherein, p_m (bar) stands for the mean applied pressure in column 7 and Q_p (m^3/h) for permeate flow. The power and specific energy terms of CP in the respective columns 10 and 11 are derived by analogy with the respective terms of HP except for the use of Q_{CP} instead of Q_f in Eq. (2) and Δp instead of p_m in Eq. (3). The term of permeate production per cycle (m^3/cycle) in column 12 is the product of the cycle time (cycle/min/60) and Q_f, and the term of cumulative sequential permeate volume (Σm^3) in column 13 is the product of the number of CCD cycles (column 2) and the volume per cycle (column 12). The total power demand at a given CCD cycle displayed in column 14 is the sum of the power components of both HP (column 8) and CP (column 10) and likewise, the overall specific energy displayed in column 15 is the sum of the terms of the individual pumps. The CCD recovery is the sequential recovery expressed by Eq. (4); wherein, ΣV_p stands for the cumulative sequential permeate volume and V for the fixed intrinsic closed circuit volume (97.1 L).

$$P_{appl} = \mu/A/T_{CF} + \Delta\pi_{av} + \Delta p/2 + p_p - \pi_p \tag{1}$$

$$P = Q_f \times p/36/\text{eff} \tag{2}$$

$$\text{Specific energy} = P/Q_p = (Q_f/Q_p) \times p_m/36/\text{eff} \tag{3}$$

$$\text{Sequential recovery} = \Sigma V_p/(\Sigma V_p + V) \times 100 \tag{4}$$

The permeate salt content (ppm) per CCD cycle in column 17 of Table 1(A) is derived from the RO salt diffusion expression in Eq. (5); wherein, B stands for the diffusion coefficient, C_f for feed concentration, and pf_{av} for the average concentration polarization factor. The average concentration polarization factor cited at the top of the table is derived by Eq. (6); wherein Y_{av} stands for the average element recovery expressed by Eq. (7), MR is the module recovery (%), and n is the

Table 1(B)
The simulated performance of 50% recovery by the compact SWRO-CCD ME2 (E = SWC6-MAX- 8´´) unit with feed of 32,000 ppm NaCl in the flux range 10–25 lmh at MR = 20% and 25˚C

	Pressure						Permeate		Production	
Flux lmh	Min. bar	Max. bar	Sequence Time minute	SWRO-CCD Recovery %	Power Max. kW	Specific Energy kWh/m^3	Mean ppm	Mean µS/cm	m^3/h	m^3/day
10.0	34.8	52.1	7.14	50.0	1.406	1.441	389	778	0.82	19.6
12.5	36.3	53.6	5.71	50.0	1.818	1.500	311	623	1.02	24.5
15.0	37.8	55.1	4.76	50.0	2.256	1.561	259	519	1.22	29.4
17.5	39.3	56.6	4.08	50.0	2.722	1.624	222	445	1.43	34.3
20.0	40.9	58.1	3.57	50.0	3.215	1.688	195	389	1.63	39.2
22.5	42.4	59.7	3.17	50.0	3.737	1.753	173	346	1.84	44.1
25.0	43.9	61.2	2.86	50.0	4.289	1.820	156	311	2.04	49.0

number of elements per module. The value of the empirical exponential coefficient (0.45) in Eq. (6) was obtained using the "beta" terms derived by an IMS Design program for ME2 (E = SWC6-MAX) under the conditions specified in Table 1(B).

$$C_p = B \times C_f \times pf_{av} \times T_{CF}/\mu \quad (5)$$

$$Pf_{av} = 10^{(0.45\times Y_{av})} \quad (6)$$

$$Y_{av} = 1 - (1 - \mathrm{MR}/100)^{1/n} \quad (7)$$

The module's concentrate-side pressure drop (Δp) in RO is the result of flow-induced pressure losses as function of the number (n) of elements per pressure vessel and their internal design characteristics as well as the average flow. The Δp value used for the appropriate calculations in Table 1(B) is derived by Eq. (8); wherein, n stands for the number of elements per pressure vessel, Q_{mi} for inlet feed flow to the pressure vessel, and Q_{mo} for outlet brine flow. Another expression for Δp that in Eq. (9) is derived from the MR expression in Eq. (10) and the Q_{mi} expression in Eq. (11), since under CCD operational conditions $Q_{HP} = Q_p$ and $Q_{mo} = Q_{CP}$. The calculated Δp data by either Eq. (8) or (9) yield similar results to those obtained by IMS design programs for ME2 (E = SWC6-MAX) under the same conditions.

$$\Delta p(\mathrm{bar}) = (8/1,000) \times n \times [(Q_{mi} + Q_{mo})/2]^{1.7} \quad (8)$$

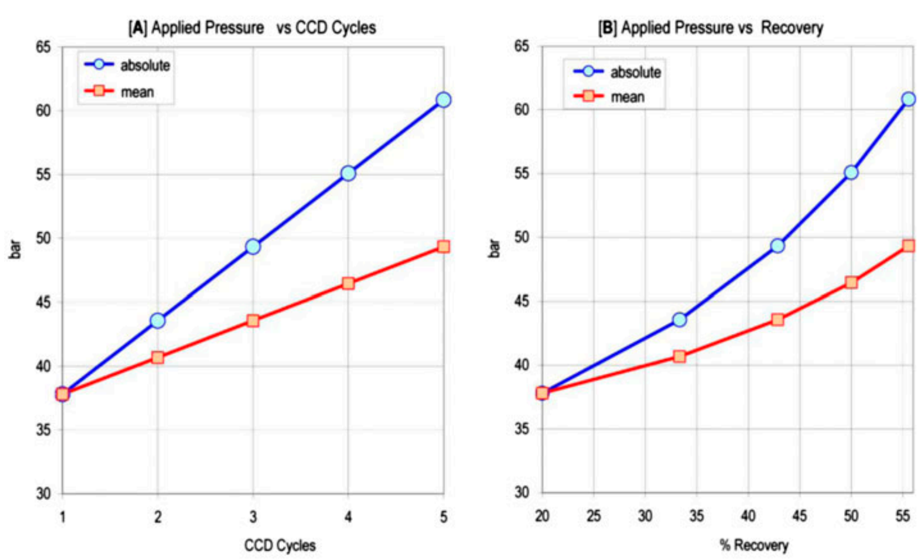

Fig. 3. Applied pressures as function of CCD cycles **[A]** and recovery **[B]** revealed during the SWRO-CCD ME2 (E = SWC6-MAX) unit performance simulation with 32,000 ppm NaCl at 15 lmh with MR = 20% described in Table 1(A).

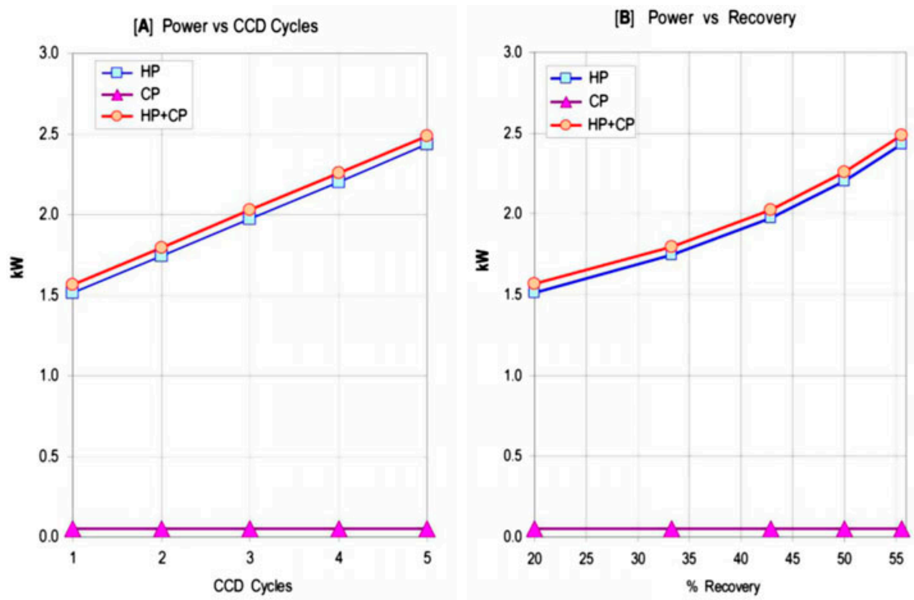

Fig. 4. Power demand of pumps as function of CCD cycles **[A]** and recovery **[B]** revealed during the SWRO-CCD ME2 (E = SWC6-MAX) unit performance simulation with 32,000 ppm NaCl at 15 lmh with MR = 0% described in Table 1(A).

$$\Delta p(\text{bar}) = (8/1,000) \times n \times [Q_{\text{mi}}/2 \times (2 - \text{MR}/100)]^{1.7} \quad (9)$$

$$\text{MR(module recovery)} = (Q_{\text{mi}} - Q_{\text{mo}})/Q_{\text{mi}} \times 100 = Q_{\text{p}}/(Q_{\text{p}} + Q_{\text{CP}}) \times 100 = Q_{\text{HP}}/(Q_{\text{HP}} + Q_{\text{CP}}) \times 100 \quad (10)$$

$$Q_{\text{mi}} = Q_{\text{HP}} + Q_{\text{CP}} = Q_{\text{p}} + Q_{\text{CP}} \quad (11)$$

The theoretical simulation results revealed in Table 1 (A) for a small compact BWRO-CCD ME2 (E = SWC6-MAX) unit operated with feed of 32,000 ppm NaCl at 15 lmh with MR = 20% are displayed graphically in Figs. 3–6. Applied pressure and mean applied pressure variations as function of CCD cycles and recovery are displayed in Fig. 3(A) and (B), respectively. Noteworthy, in particular, is the sequential pressure boosting

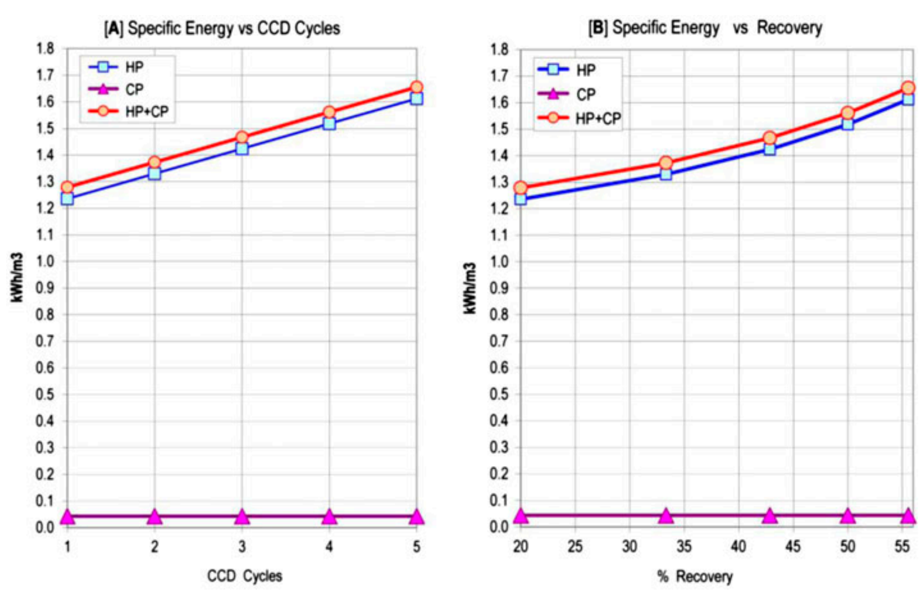

Fig. 5. Specific energy of desalination as function of CCD cycles **[A]** and recovery **[B]** revealed during the SWRO-CCD ME2 (E = SWC6-MAX) unit performance simulation with 32,000 ppm NaCl at 15 lmh with MR = 20% described in Table 1 (A).

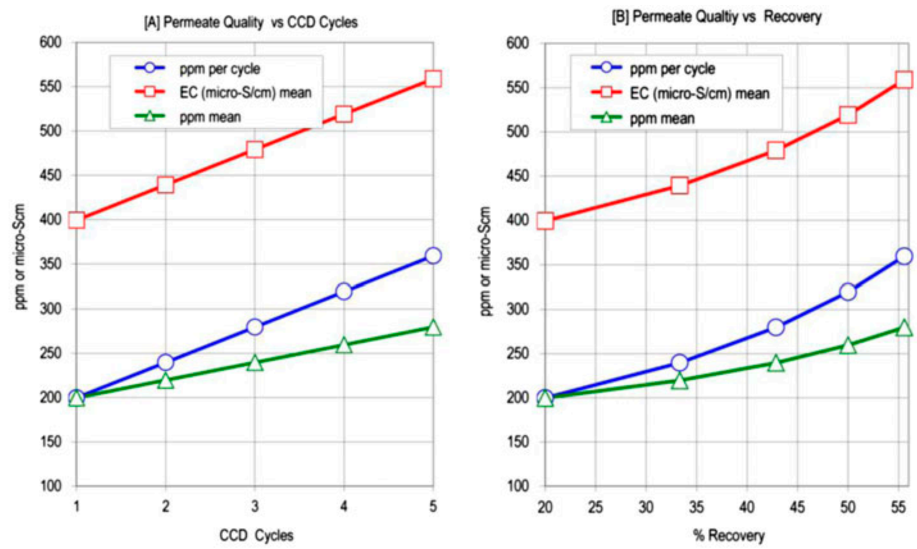

Fig. 6. Permeate salinity and EC as function of CCD cycles [**A**] and recovery [**B**] revealed during the SWRO-CCD ME2 (E = SWC6-MAX) unit performance simulation with 32,000 ppm NaCl at 15 lmh with MR = 20% described in Table 1(A).

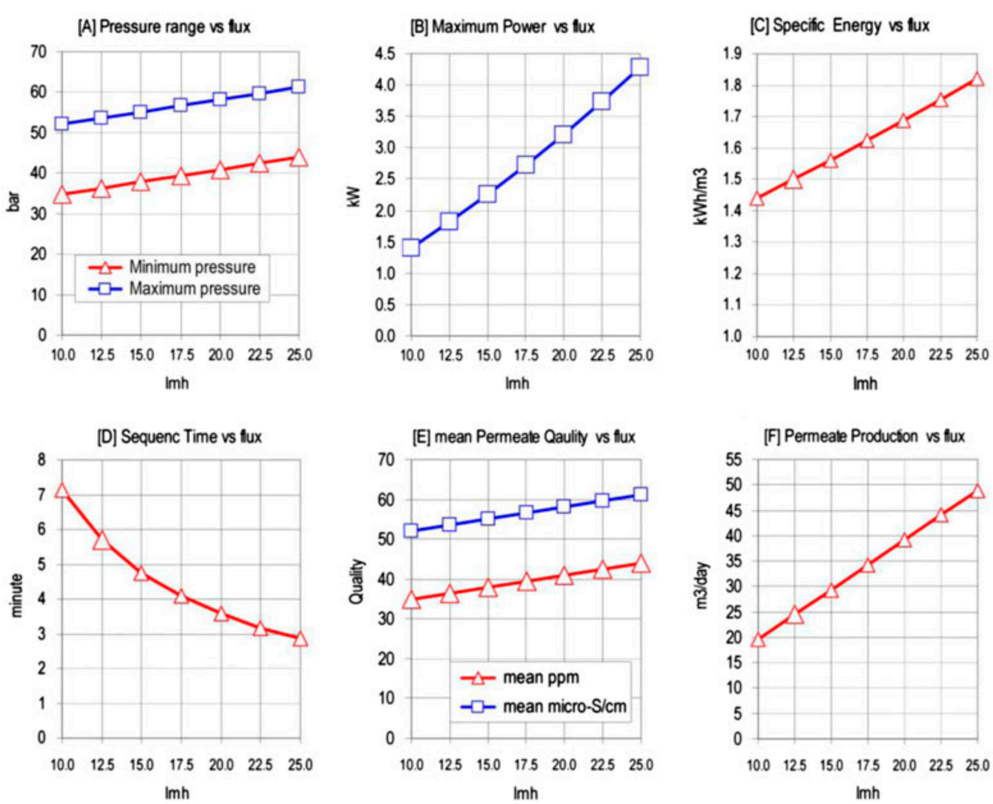

Fig. 7. Performance variability of 50% recovery in the flux range 10–25 lmh by the SWRO-CCD ME2 (E = SWC6-MAX-8´´) unit with 32,000 ppm NaCl at MR = 20% and 25˚C according to the data in Table 1(B) in reference to applied pressures [**A**], power [**B**], specific energy [**C**], sequence time [**D**], permeate salinity and EC [**E**] and permeate daily production [**F**].

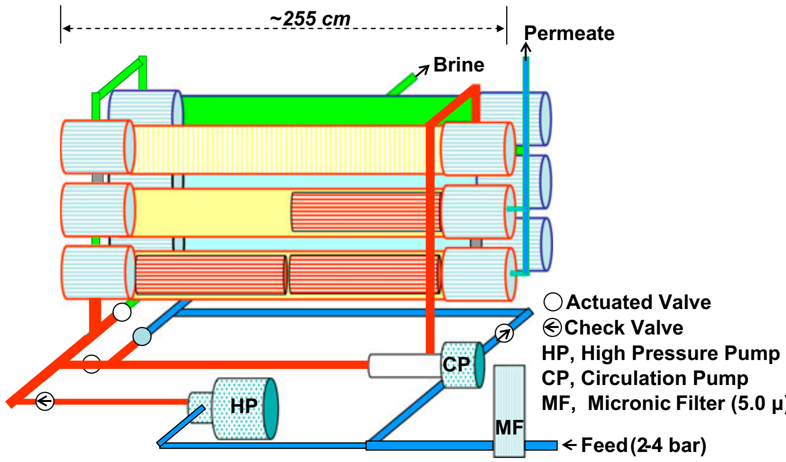

Fig. 8. A schematic illustration of a compact SWRO-CCD ME3 unit design comprising a split single module of three elements (8´´) with free space and a SC of the same split pressure vessels configuration.

effect achieved under the fixed flux and variable pressure conditions of the CCD process whereby exceptionally low desalination energy is required without need for ER means. Sequential power demand variations of pumps (HP and CP) as function of CCD cycles and recovery are displayed in Fig. 4(A) and (B), respectively. The sequential specific energy variations as function of CCD cycles and recovery are displayed in Fig. 5(A) and (B), respectively. The exceptionally low specific energies revealed by simulation in Fig. 5 are consistent with experimental results already reported [7–10] in the context of the SWRO-CCD technology. Absolute and mean permeate salinity sequential variations as function of CCD cycles and recovery are displayed in Fig. 6(A) and (B), respectively, and the results manifest the expected rise of salinity with recovery.

The versatile performance characteristics of 50% recovery in the flux range 10–25 lmh by the SWRO-CCD ME2 (E = SWC6-MAX-8´´) unit with 32,000 ppm NaCl at MR = 20%, and 25˚C are revealed in Table 1(B) and by the graphical presentation of the results in Fig. 7 in reference to applied pressures **[A]**, power **[B]**, specific energy **[C]**, sequence time **[D]**, permeate salinity and EC **[E]**, and permeate production rates **[F]**. In spite of its small dimensions of 170 × 100 × 150 (length–width–height), the SWRO-CCD ME2 unit under review can be operated at 50% over a wide flux range (10–25 lmh) with exceptionally low energy consumption (1.406–1.820 kWh/m^3) without need of ER means and provide considerable amounts of permeates (19.6–49.0 m^3/d or 0.82–2.04 m^3/h) whose qualities (778–311 μS/cm) are essentially a function of flux.

The flexible relationships between flux (10–25 lmh), production rate (19.6–49.0 m^3/d), and maximum power demand of pumps (1.406–4.289 kW) revealed in Table 1(B) are noteworthy in particular, since they imply the facile integration of the ME2 unit with clean renewable energy sources (e.g. solar panels and/or small wind turbines) of variable power output for high recovery (50%) seawater desalination as function of power availability—in simple terms, greater power availability will induce higher flux of increased permeate production and vice versa with significant energy efficiency not possible by any existing SWRO technique. The unit under review can be made by simple means to operate by various modes such as with grid power if available and/or with solar panels and/or with small wind turbines. Solar panels and small wind turbines are commercially available and have became rather inexpensive in recent years and this

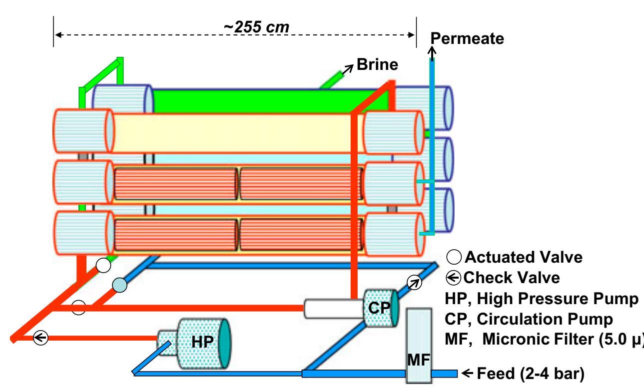

Fig. 9. A schematic illustration of a compact of SWRO-CCD ME3 unit design comprising a split single module of four elements (8´´) with free space and a SC of the same split pressure vessels configuration.

Table 2(A)
The simulated performance of the compact SWRO-CCD ME3 (E = SWC6-MAX-8´´) unit with feed of 32,000 ppm NaCl at fixed flux of 15 lmh, MR = 25% and 25˚C with up to 62.5% recovery

TEST - SWC6 MAX		UNIT DESIGN		CCD Parameters		Temperature	
40.8	m2/Element	1	Modules	3.20	% Initial feed	≥25 25 °C	≤25 25 °C
25	m3/day	3	Elements/Module	15.0	lmh Flux	≥25 1.000 TCF	≤25 1.000 TCF
32,000	ppm NaCl	690	cm long PV	1.84	m3/h Permeate (= Q_{HP})		
41	bar Applied Pressure	20	cm diameter PV	25	% Module Recovery	C≥25°C	
10	% Recovery	15	liter element volume	5.51	m^3/h Qcp	TCF=EXP[**2640**(1/298-1/(273+C)]	
25	Centig.	5	% lines volume			C≤25°C	
99.60	% Salt Rejection	180.2	liter per module	0.57	bar Δp	TCF=EXP[**3020**(1/298-1/(273+C)]	
15.08	bar NDP	180.2	liter per design	8.3	psi Δp		
25.531	l/m2/h Flux			1.96	min/cycle CCD	**Pumps**	
1.693	l/m2/h/bar -A			0.091	av-MR/Element-CCD	0.85 HP *eff*.	
0.080	l/m2/h - B			1.032	av-pf - CCD*	0.75 CP *eff*.	

π(bar)-C(%)

32000	ppm NaCl Feed	25.60	bar Osmotic Pressure	8.00	π(bar)/C(%)

ME2 MODULE DATA				CCD Sequence Cycles							CCD Sequence Combned Data					PERMEATE			
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Energy		REC	Cycle		mean	
Mode	Step	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	μS/cm
CCD	1	3.20	4.27	1.96	39.0	39.0	2.341	1.275	0.116	0.063	0.060	0.060	2.456	1.338	25.0	206	412	206	412
CCD	2	4.00	5.33	3.93	46.5	42.7	2.789	1.397	0.116	0.063	0.060	0.120	2.904	1.460	40.0	257	515	232	463
CCD	3	4.80	6.40	5.89	53.9	46.5	3.237	1.519	0.116	0.063	0.060	0.180	3.352	1.582	50.0	309	618	257	515
CCD	4	5.60	7.47	7.85	61.4	50.2	3.685	1.641	0.116	0.063	0.060	0.240	3.800	1.704	57.1	360	721	283	566
CCD	5	6.40	8.53	9.82	68.9	53.9	4.133	1.763	0.116	0.063	0.060	0.300	4.248	1.826	62.5	412	824	309	618
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

may suggest that their integration with the compact SWRO-CCD ME2 unit under review will enable exceptionally low-cost seawater desalination with a fast investment return period especially in remote regions where electricity is expensive, since energy consumption accounts to some 50–70% of the desalination costs with small units.

4. Compact SWRO-CCD units of ME3 and ME4 configurations

Expansion of the SWRO-CCD single module compact unit design to greater permeate production capacity can be achieved by the use of longer split pressure vessels and additional elements and such an approach is illustrated by the schematic design of the ME3 unit in Fig. 8 and the ME4 unit in Fig. 9. The simulated performance of the compact SWRO-CCD

Table 2(B)
The simulated performance of 50% recovery by the compact SWRO-CCD ME3 (E = SWC6-MAX- 8´´) unit with feed of 32,000 ppm NaCl in the flux range 10–25 lmh at MR = 25% and 25˚C

	Pressure						Permeate		Production	
Flux lmh	Min. bar	Max. bar	Sequence Time minute	SWRO-CCD Recovery %	Power Max. kW	Specific Energy kWh/m^3	Mean ppm	Mean μS/cm	m^3/h	m^3/day
10.0	35.9	50.8	8.84	50.0	2.073	1.449	386	772	1.22	29.4
12.5	37.5	52.4	7.07	50.0	2.690	1.514	309	618	1.53	36.7
15.0	39.0	53.9	5.89	50.0	3.352	1.582	257	515	1.84	44.1
17.5	40.6	55.5	5.05	50.0	4.061	1.652	221	441	2.14	51.4
20.0	42.1	57.1	4.42	50.0	4.818	1.724	193	386	2.45	58.8
22.5	43.7	58.7	3.93	50.0	5.625	1.798	172	343	2.75	66.1
25.0	45.3	60.2	3.53	50.0	6.484	1.875	154	309	3.06	73.4

Table 3(A)
The simulated performance of the compact SWRO-CCD ME4 (E = SWC6-MAX-8´´) unit with feed of 32,000 ppm NaCl at fixed flux of 15 lmh, MR = 30% and 25˚C with up to 68.2% recovery

TEST - SWC6 MAX

40.8	m2/Element
25	m3/day
32,000	ppm NaCl
41	bar Applied Pressure
10	% Recovery
25	Centig.
99.60	% Salt Rejection
15.08	bar NDP
25.531	l/m2/h Flux
1.693	l/m2/h/bar -A
0.080	l/m2/h - B

UNIT DESIGN

1	Modules
4	Elements/Module
690	cm long PV
20	cm diameter PV
15	liter element volume
5	% lines volume
164.5	liter per module
164.5	liter per design

CCD Parameters

3.20	% Initial feed
15.0	lmh Flux
2.45	m3/h Permeate (=Q_{HP})
30	% Module Recovery
5.71	m^3/h Qcp
0.86	bar Δp
12.6	psi Δp
1.73	min/cycle CCD
0.085	av-MR/Element-CCD
1.030	av-pf - CCD*

Temperature

≥25	25	°C	≤25	25	°C
≥25	1.000	TCF	≤25	1.000	TCF

C≥25°C
TCF=EXP[**2640**(1/298-1/(273+C)]
C≤25°C
TCF=EXP[**3020**(1/298-1/(273+C)]

Pumps

0.85	HP *eff*.
0.75	CP *eff*.

π(bar)-C(%)

32000 ppm NaCl Feed | 25.60 bar Osmotic Pressure | 8.00 π(bar)/C(%)

ME2 MODULE DATA				CCD Sequence Cycles							CCD Sequence Combned Data					PERMEATE			
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Power & Energy		REC	Cycle		mean	
Mode	Step	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	μS/cm
CCD	1	3.20	4.57	1.73	40.4	40.4	3.230	1.319	0.182	0.074	0.070	0.070	3.412	1.394	30.0	214	428	214	428
CCD	2	4.16	5.94	3.46	49.7	45.0	3.976	1.472	0.182	0.074	0.070	0.141	4.158	1.546	46.2	278	556	246	492
CCD	3	5.12	7.31	5.18	59.0	49.7	4.722	1.624	0.182	0.074	0.070	0.211	4.904	1.699	56.3	342	685	278	556
CCD	4	6.08	8.69	6.91	68.4	54.4	5.468	1.777	0.182	0.074	0.070	0.282	5.650	1.851	63.2	406	813	310	620
CCD	5	7.04	10.06	8.64	77.7	59.0	6.214	1.929	0.182	0.074	0.070	0.352	6.396	2.003	68.2	471	941	342	685
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

ME3 (E = SWC6-MAX-8´´) unit (Fig. 8) with feed of 32,000 ppm NaCl at fixed flux of 15 lmh, MR = 25%, and 25˚C up to 62.5% recovery is described in Table 2 (A) and its simulated performance results of 50% recovery over the flux range 10–25 lmh are revealed in Table 2(B) and illustrated as function of flux in Fig. 10. Likewise, the simulated performance of the compact SWRO-CCD ME4 (E = SWC6-MAX-8´´) unit (Fig. 9) with feed of 32,000 ppm NaCl at fixed flux of 15 lmh, MR = 30%, and 25˚C up to 68.2% recovery is described in Table 3(A) and its simulated performance results of 56.3% recovery over the flux range 10–25 lmh revealed in Table 3(B) and illustrated as function of flux in Fig. 11. The ME3 and ME4 units are both of the same estimated dimensions [270 × 100 × 150 (length–width–height)] and their flux-dependent (10–25 lmh) respective production ranges are 29.4–73.4 m^3/d and 39.2–97.9 m^3/d. Compared with ME2, the production of the ME3 unit is 50% greater and that of ME4 is twice.

Table 3(B)
The simulated performance of 56.3% recovery by the compact SWRO-CCD ME4 (E = SWC6-MAX- 8´´) unit with feed of 32,000 ppm NaCl in the flux range 10–25 lmh at MR = 30% and 25˚C

	Pressure		Sequence	SWRO-CCD	Power	Specific	Permeate		Production	
flux	Min.	Max.	Time	Recovery	Max.	Energy	Mean	Mean		
lmh	bar	bar	minute	%	kW	kWh/m^3	ppm	μS/cm	m^3/h	m^3/day
10.0	37.2	55.9	7.78	56.3	3.040	1.558	417	834	1.63	39.2
12.5	38.8	57.4	6.22	56.3	3.940	1.627	334	668	2.04	49.0
15.0	40.4	59.0	5.18	56.3	4.904	1.699	278	556	2.45	58.8
17.5	42.0	60.6	4.44	56.3	5.935	1.773	238	477	2.86	68.5
20.0	43.6	62.3	3.89	56.3	7.036	1.851	209	417	3.26	78.3
22.5	45.2	63.9	3.46	56.3	8.211	1.931	185	371	3.67	88.1
25.0	46.9	65.5	3.11	56.3	9.461	2.014	167	334	4.08	97.9

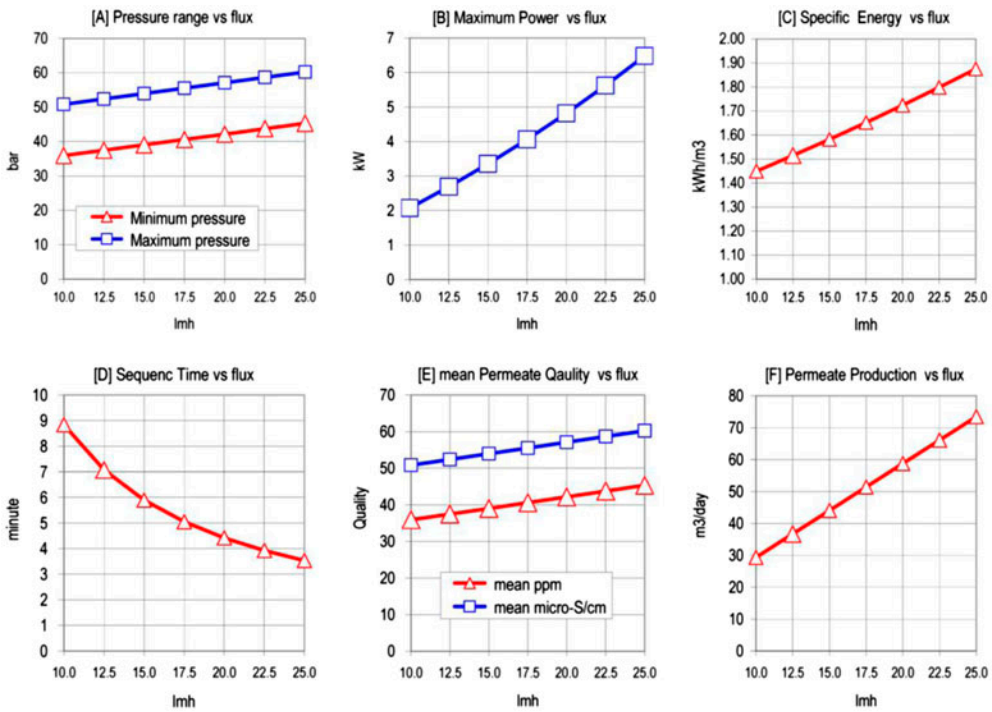

Fig. 10. Performance variability of 50% recovery in the flux range 10–25 lmh by the SWRO-CCD ME3 (E = SWC6-MAX-8´´) unit with 32,000 ppm NaCl at MR = 25% and 25˚C according to the data in Table 2(B) in reference to applied pressures [**A**], power [**B**], specific energy [**C**], sequence time [**D**], permeate salinity and EC [**E**] and permeate daily production [**F**].

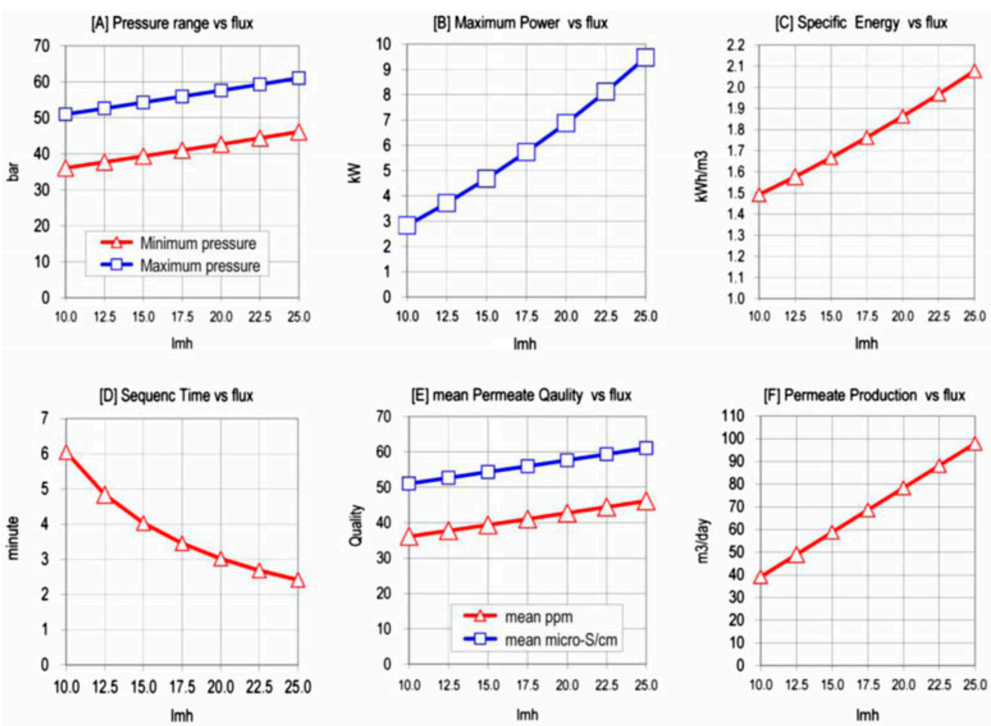

Fig. 11. Performance variability of 56.2% recovery in the flux range 10–25 lmh by the SWRO-CCD ME4 (E = SWC6-MAX-8´´) unit with 32,000 ppm NaCl at MR = 30% and 25˚C according to the data in Table 3(B) in reference to applied pressures [**A**], power [**B**], specific energy [**C**], sequence time [**D**], permeate salinity and EC [**E**], and permeate daily production [**F**].

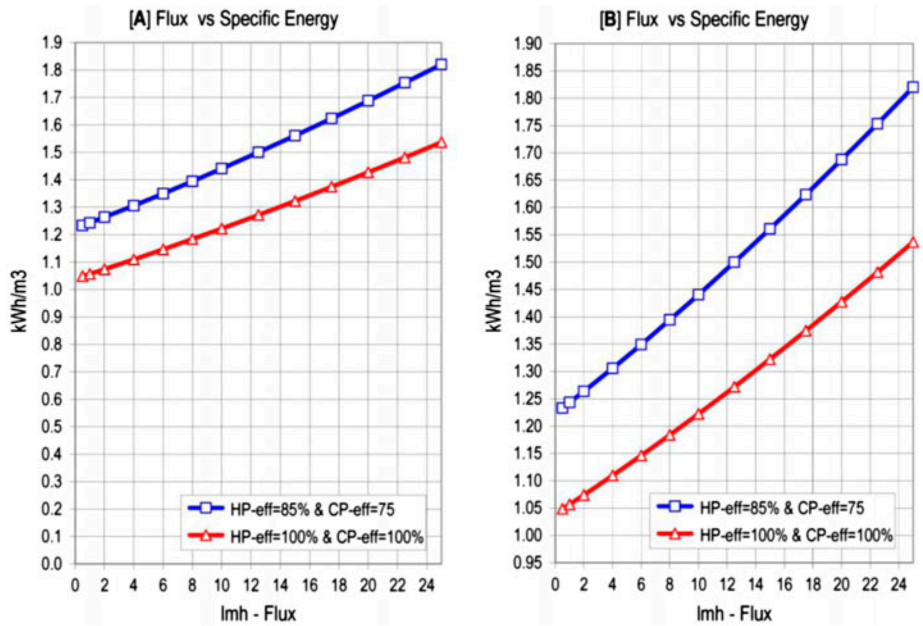

Fig. 12. Simulated energy in the flux range 0.5–25.0 lmh for 50% recovery of 32,000 ppm NaCl with MR = 20% at 25°C of the compact SWRO-CCD ME2 (E = SWC6-MAX-8´´) unit are revealed on a full energy scale **[A]** and an expanded energy scale **[B]** for HP-*eff* = 85% and CP-*eff* = 75% as well as for absolute efficiency (100%)of both pumps.

5. Discussion

SWRO-CCD is a consecutive sequential desalination technology performed with fixed flow under variable pressure conditions by concentrate recycling in closed circuit and it mixing with fresh feed at inlet to modules with occasional brine replacement by fresh pressurized feed through the engagement of a SC by a process of negligible brine energy loss. CCD is a continuously flow-staged and pressure-boosted technology with recovery determined by the selected maximum variable pressure of operation irrespective of the number of elements per module, and this in contrast with conventional SWRO where recovery is a function of the number of elements per module. The aforementioned considerations provided the incentives for the evaluation of the CCD technology for small compact single module units of MEn (n = 2–4) configuration described in the current work. The results of the current study confirmed the superb performance characteristics of the analyzed single module SWRO-CCD MEn (n = 2–4) units as well as the ability to create highly compact units without loss of performance effectiveness using wide spread common components such as 8´´ pressure vessels and elements. The noteworthy features of the compact SWRO-CCD MEn (n = 2–4) units under review in this study include simple designs made of common components; compact designs of small foot print and space volume, exceptionally low energy consumption without need of ER unmatched by any existing technique; flexible flux operation over a wide range (10–25 lmh); flexible recovery determined only by the maximum variable pressure irrespective of the number of elements per pressure vessel and/or the operational flux; flexible cross-flow selection independent of flux and/or recovery; and simple operational control means by few set-points which may be changed "on-line" without need to stop desalination whereby an infinite number of combinations are made available for process optimization.

The compact size of the SWRO-CCD MEn (n = 2–4) units is evident by their projected dimensions of 170 × 80 × 150 cm (length–width–height) for the ME2 unit and 270 × 100 × 150 cm for the ME3 and ME4 units. These projected dimensions translate to ground footprint of 1.36 m^2 for ME2 and 2.70 m^2 for ME3 and ME4 as well as to space volume of 2.04 and 4.05 m^3, respectively. The permeate production ranges of said units as function of the selected operational flux (10–25 lmh) are 19.6–49.0 m^3/d for ME2 (Table 1(B)), 29.4–73.4 m^3/d for ME3 (Table 2(B)), and 39.2–97.9 m^3/d for ME4 (Table 3 (B)), and these maximum figures at flux of 25 lmh imply the daily water supply needs of some 490, 730, and 979 residents assuming an average consumption of 100 L per day per person. The respective units may supply the drinking and cooking needs of much greater communities of 4,900, 7,300, and 9,790 residents assuming that such needs amount to 10 L per day per person. The above cited figures imply that small of even medium size communities along the shore-lines could provide their entire water needs, or at least their entire drinking and cooking water needs, by small compact SWRO-CCD units with feed drawn from shallow beach well without need of extensive infrastructure and/or dependence on external suppliers. The exceptionally low energy consumption of the compact units under review provides another incentive for their extensive use in remote coastal regions where electricity is expensive since produced by means of small diesel-engine generators.

The energy consumption of the compact units under review in the specified flux range 10–25 lmh is revealed in Table 1(B) for 50% recovery of ME2 (1.441–1.870 kWh/m^3), Table 2(B) for 50% recovery of ME3 (1.449–1.875 kWh/m^3), and Table 3(B) for 56.3% recovery of ME4 (1.559–2.014 kWh/m^3). In fact, all three units operate with comparable energies and the higher energy range of ME4 is just a manifestation of the higher recovery of 56.3 instead of 50%. The comparable energies of all three units are evident from the simulations at 15 lmh presented in Table 1(A) for ME2 (1.561 kWh/m^3 at 50% recovery), Table 2(A) for ME3 (1.582 kWh/m^3 at 50% recovery), and Table 3(A) for ME4 (1.546 kWh/m^3 at 46.2% recovery and 1.699 kWh/m^3 at 56.3% recovery). The cited SWRO-CCD energy terms are for 32,000 ppm NaCl and derived from the simulations data base conditions displayed in Tables 1(A), 2(A) and 3(A) wherein the efficiency of HP and CP are 85% and 75%, respectively. The osmotic pressure of 32,000 ppm NaCl at 25˚C is equivalent to that of typical Ocean seawater of 35,000 ppm and therefore, the simulations results presented hereinabove with said sodium chloride solution are representative of typical Ocean seawater.

In order to ascertain the theoretical minimum energy requirement for 50% recovery of 32,000 ppm NaCl with the SWRO-CCD ME2 unit displayed in Fig. 2(A), the simulation data base in Table 1(A) was applied to generate the specific energy under flux of values 0.5; 1.0; 2.0; 4.0; 6.0; 8.0; 10.0; 12.5; 15.0; 17.5; 20.0; 22.5, and 25.0 lmh, and the results of this analysis for HP-*eff* = 85% and CP-*eff* = 75% as well as for absolute efficiency (100%) of both pumps are displayed in Fig. 12 on a full energy scale (Fig. 12(A)) and an expanded energy scale (Fig. 12(B)). The extrapolated energy results in Fig. 12 under near-zero flux conditions are near 1.24 kWh/m^3 for 50% recovery with HP-*eff* = 85% and CP-*eff* = 75% and near 1.05 kWh/m^3 with absolute efficiency (100%) of both pumps. According to Elimelech and Phillips [6], "the theoretical minimum energy of desalination for seawater at 35,000 ppm (ppm) salt and a typical recovery of 50% is 1.06 kWh/m^3" and since 32,000 ppm NaCl and typical Ocean seawater of 35,000 ppm exhibit the same osmotic pressure, the simulated results revealed in Fig. 12 imply that the new compact ME2 unit under review operates at near the theoretical minimum energy level well below the 2.5–3.5 kWh/m^3 energy range reported for some large advanced desalination plants operated with the Mediterranean (~40,000 ppm) seawater [2–4] and Ocean (~35,000 ppm) seawater [4,5] feed. The simulated energy results for ME2 (E = SWC6) are consistent with the experimental data reported [7–9] for the SWRO-CCD 4MEn (n = 1–4) experimental units with SWC6 elements in the context of Mediterranean (41,000 ppm) seawater desalination and their extrapolation to Ocean seawater. For instance, the normalized (25˚C; 85% *eff* of HP and 60% *eff* of CP) experimental energy results for 50% recovery of Mediterranean seawater with the SWRO-CCD 4ME4 unit at flux of ~13 lmh revealed ~1.80 kWh/m^3 with modeling projections [10] of ~1.65 kWh/m^3 for typical Ocean seawater (3.5%). The good consistency between the experimental and simulated results found for the SWRO-CC MEn units confirms the validity of the simulations for the compact units discussed hereinabove and implies that such units will perform at near the theoretical minimum energy level without need of ER means which at present time is not possible by any other desalination technology.

Compact single module SWRO-CCD MEn (n = 2–4) units of low energy high recovery for seawater desalination under variable flux conditions are of clear interest for many coastal communities with population up to 1000 residents where electricity is produced by diesel-engine generators and/or where grid electricity is expensive. The low energy of the compact desalination units under review should enable small coastal communities worldwide to supply their own water need at considerable saving in energy which accounts to 40–60% of the desalination costs. Moreover, the new units under review could be integrated by simple means with renewable energy sources such as those derived from inexpensive solar panels and/or small wind turbines and thereby, utilize free and clean natural energy for exceptionally low-cost desalination. The compact units under review may cope with the variable power output of the cited natural sources by adjusting the flux of operation to the power output of the source, and this requires rather simple means in the control board of the units in order to translate "on-line" power availability at inlets to units to flux and cross flow and thereby, maintain the desired module recovery (MR) of operation. In the CCD technology, the recovery is independent of flux and therefore, such compact units could be operated with high recovery even under reduced flux conditions. Solar panels and small wind turbines have became rather inexpensive in recent years and the integration of both to the same compact unit would enable all day round desalination with increased production during day time. Wind power availability in coastal regions is normally steady and good and this imply ample of free clean energy for water desalination in such regions. In contrast with SWRO-CCD, the attainment of low energy, high recovery, and flexible operational flux by convention SWRO techniques is an impossible task which makes the former method the only viable technology for such an application.

6. Concluding remarks

The data presented in this paper describe the design and performance characteristics of single module (8´´) SWRO-CCD MEn (n = 2–4) units of compact size for daily desalination of up to 100 m^3 with low energy and high recovery under variable flux condition. The energy requirements of said units are shown to be at the theoretical minimum level without need of energy recovery means, a feature not possible by any other technique. The attainment of high recovery by said units are shown to be independent of the number of elements per module, a feature not possible by any other technique. The units under review are demonstrated to operate under variable flux conditions without exceeding the elements' performance characteristics recommended by their manufacturers. The new compact units under review are intended flow low-cost desalination in coastal region worldwide and could be coupled by simple means with renewable energy sources such as solar panels and small wind turbines and thereby, utilize free and clean natural energy for exceptionally low-cost seawater desalination in coastal regions worldwide.

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