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CCD Series No-10: small compact BWRO closed-circuit desalination (CCD) units of high-recovery, low-energy and reduced fouling for supplied water upgrade to industry, irrigation, domestic, and medical applications

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ABSTRACT

The recently emerging new closed circuit desalination (CCD) technology enables performing high-recovery and low-energy BWRO desalination of reduced fouling irrespective of the number of elements per module and thus opened the door to a new class of small compact units for diverse applications. The design aspects and performance prospects of such small compact BWRO-CCD units (<5.4 m^3/h; <130 m^3/d) are illustrated with modules comprising either two or three elements each (MEn with $n = 2$–3). Since small compact BWRO units are extensively used for supplied water upgrade to industry, irrigation, domestic and medical applications, the unique performance characteristics of said small compact CCD units of high recovery and low energy is exemplified with feed of 200–750 ppm NaCl which cover the range of 230–900 ppm of ordinary supplied water sources worldwide. The supplied water upgrade by said compact CCD units are illustrated at the level of a single-pass quality permeates as well as at the level of double-pass quality permeates of exceptionally low salinity in the range 0.13–1.54 ppm depending on the feed salinity and the membrane salt rejection characteristics. The double-pass process in these compact CCD units implicate the use of first pass permeates as feed to the second pass, thereby enabling the same unit execute either a single or a double-pass process depending on the desired quality of permeate.

Keywords: CCD; BWRO; Small compact RO units; High recovery; Low energy; Reduced fouling; Upgrade of water supplies

1. Introduction

The general global trend of declined quality of ground and underground water sources coupled with the increased demand of water quality for domestic, industrial, and agricultural applications have led over the years to the increased role of BWRO in water treatment procedures. The BWRO world markets split broadly into well-documented common units with permeates production >10 m^3/h (>240 m^3/h) and the other of undocumented small units of <10 m^3/h (<240 m^3/h) which are extensively used everywhere worldwide for diverse applications. Small compact BWRO units (<5 m^3/h; <120 m^3/d) are used in many rural regions worldwide with inadequate ground/underground water sources for domestic supply of drinking water to avoid epidemics. Special needs for small compact mobile BWRO units arise during floods, earthquakes, and other major disasters to enable fast supply of drinking water to isolated communities as well as for military use in regions of questionable water quality. Modern "green house" agriculture makes use of small compact BWRO units for controlled irrigation and dedicated small compact units are utilized by industry at large (e.g. drug, hygiene, food, beverage, paper, fabric, printing, detergent, chemical, electronic, semi-conductors, etc) where the quality of water is an essential ingredient in production processes. A noteworthy application of small compact BWRO units (1–5 m^3/h) is found in area of medical dialysis that is provided with increased demand in tenth of thousands of hospitals and dedicated dialysis centers spread worldwide. Small compact BWRO units are required with increased demand for water upgrade of feed to modest size steam supply boilers. Compact BWRO units are frequently produced by small companies and esoteric subcontractors, and therefore, a reliable assessment of their market size is none trivial in spite of its obvious existence everywhere for wide range applications. In Israel alone, a country with population of seven millions, small compact BWRO unit are offered by at least 10 different entities, and this implies by extrapolation the existence of at least 10,000 producers worldwide of such units including in underdeveloped countries where small units are widely used for the supplies of drinking water. The commercial availability small diameter pressure vessels and membrane elements by all major producers of such items is just another manifestation of the market enormity of the small compact BWRO units for various diverse applications.

The rapid depletion and/or deterioration ground and underground water sources and the need for enhanced pretreatment cause the steady rise in costs of domestic waters, and therefore, their subsequent upgrade for specific applications should be done economically by high-recovery and low-energy BWRO processes. High-recovery low-energy BWRO in the context of small compact conventional units is complicated by the need for staging and energy recovery means. Recovery in conventional plug flow desalination (PFD) BWRO processes proceeds as function of the number of head to tail lined elements and energy saving in such processes is achieved by energy recovery means one of which the so-called turbocharger. For instance, conventional BWRO of 80 ± 5% recovery with reasonable energy consumption requires a unit design [1] with a line of 12 elements in a 2–1 staged pressure vessels design (6 elements per PV) and turbocharger means for the recycling of brine energy. Likewise, conventional BWRO of 90% recovery with reasonable energy consumption requires a unit design [1] with a line of 18 elements in a 4–2-1 staged pressure vessels design (6 elements per PV) and turbocharger means. The aforementioned staging requirements of conventional BWRO to increase recovery are irrespective of size of units and one approach to enable compact BWRO units of high recovery implicates small diameter pressure vessels and elements (e.g. 2.5´´ and 4.0´´ instead of 8.0´´) that are commercial availability from all major producers of pressure vessels and membrane elements.

The recently emerging new closed circuit desalination (CCD) technology [2–11] of high-recovery and low-energy BWRO irrespective of the number of elements per module is noteworthy in particular in the context of small compact units for diverse applications, a subject matter to be discussed hereinafter. The BWRO-CCD technology [3,7,10] takes place by internal concentrate recycling with occasional replacement of brine by fresh feed and is characterized by high-recovery, low-energy consumption without need of energy recovery, reduced fouling (scaling and/or biofouling) and flexible control. CCD is essentially a batch process made continuous by occasional replacement of brine with fresh feed without stopping desalination and recovery in this two-step consecutive sequential process is a function of recycling irrespective of the number of elements per module—more recycling concomitant with higher recovery and vice versa. The low-energy demand of the two-step (CCD and PFD) consecutive sequential process arises from the near absolute energy conversion efficiency during the CCD cycles with identical flow rates of pressurized feed and permeate without loss of any brine energy combined with occasional brief PFD steps under reduced pressure for brine replacement by fresh feed. The ability to reach high recovery with low energy irrespective of the number of elements per pressure vessel and without need for staging opened the door for the first time to the design of highly effective small compact BWRO-CCD units for diverse applications.

Desalination of brackish water by CCD instead of conventional (PFD) techniques represents a new conceptual approach to desalination that is fully consistent with the theoretical principles and engineering aspects associated with design of RO units irrespective of size and/or nature of application. The conceptual development of an effective small compact

BWRO-CCD unit technology from theory to practice is outlined and exemplified hereinafter.

2. Small compact BWRO-CCD units of ME2 and ME3 module configurations

The schematic ME2 design displayed in Fig. 1 illustrates a typical compact BWRO-CCD unit comprising 2 elements (8´´) arranged in line (tail to head) inside a split pressure vessel (2 × 130 = 260 cm total length) equipped with feed pressurizing (HP-*vdf*) and concentrate recycling (CP) means, conducting lines (solid gray), micronic-filter (MF), actuated valve (AV), manual valve (MV), check valve (CV), pressure monitor (PM) of pressurized feed, pressure difference gauge (PDG), air release valve (ARV), conductivity monitor (CM_p), and flow monitor (FM_p) of permeate as well as flow monitor of feed (FM_f). The concentrate recycling pump (CP) in the basic design displayed in Fig. 1 is intended for full power (50 or 60 Hz) operation with flow rate determined by Δp and the adding of *vfd* to CP and FM to the recycle concentrate line will enable complete control of cross flow and provide means for the selection of a desired module recovery (MR). The horizontal pressure vessels in the design displayed in Fig. 1 could be positioned vertically without adverse operational effects. Lines, valves, and pressure vessels in the design displayed in Fig. 1 for the upgrade of supplied water (<1.500 ppm) could be made of PVC with 15 bar pressure rating, or other suitable plastic materials instead. The average permeate production of the unit under review at an operational flux of 25 lmh is in the range of 45 ± 5 m^3/day (1.8 ± 0.2 m^3/h) depending on the choice of membrane elements.

The schematic ME3 design displayed in Fig. 2 illustrates a typical compact BWRO-CCD unit comprising 3 elements (8´´) arranged in line (tail to head) inside a split pressure vessel (3 × 130 = 390 cm total length) equipped with the same components as already described in Fig. 1. The ME3 unit in Fig. 2 is intended for permeate production of 65 ± 5 m^3/day (2.7 ± 0.2 m^3/h) at flux of 25 lmh depending on the choice of membrane elements. The addition of a second spit module to the ME2 design in Fig. 1 yields the 2ME2 configuration in Fig. 3 for an average permeate production of 90 ± 5 m^3/day (3.8 ± 0.2 m^3/h) at flux of 25 lmh depending on the choice of membrane elements. Likewise, the adding of a second spit module to the ME3 design in Fig. 2 yields the 2ME3 configuration in Fig. 4 for an average permeate production of 130 ± 5 m^3/day (5.4 ± 0.2 m^3/h) at flux of 25 lmh depending on the choice of membrane elements. The use of 4´´ instead of 8´´ diameter modules in the designs displayed in Figs. 1 and 3 enables the design of compact units for the average permeate production of ~10 m^3/day (~420 liter/h) and ~20 m^3/day (~840 liter/h), respectively. Likewise, the use of 4´´ instead of 8´´ diameter modules in the designs displayed in Figs. 2 and 4 enables the design of small compact units for the average permeate production of ~14 m^3/day (~580 liter/h) and ~28 m^3/day (~1,160 liter/h), respectively. The aforementioned small compact BWRO-CCD units for permeate production in the range of 400–55,500 liter/hour are intended to enable cost-effective upgrade of water supplies (<1,500 ppm) for industry, "green-house" irrigation, domestic use, and medical dialysis with high-recovery (>90%) and low-energy

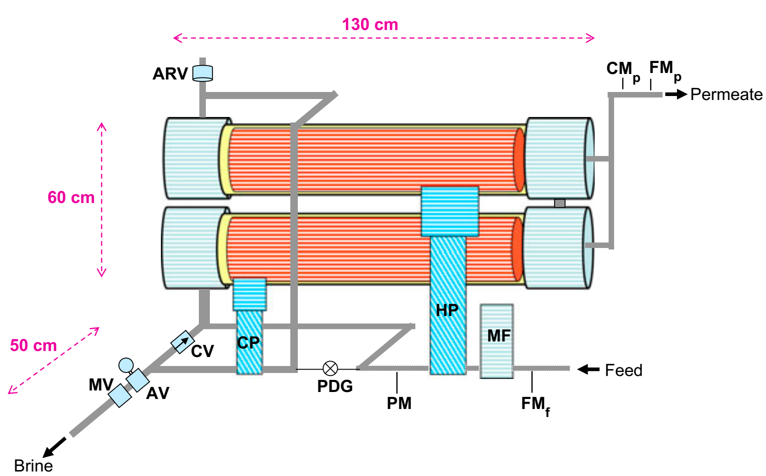

Fig. 1. A schematic design of a small compact BWRO-CCD unit with ME2 configuration comprising a single split module of 2 elements (8´´) for permeate production of 1.9 m^3/h at 25 lmh.

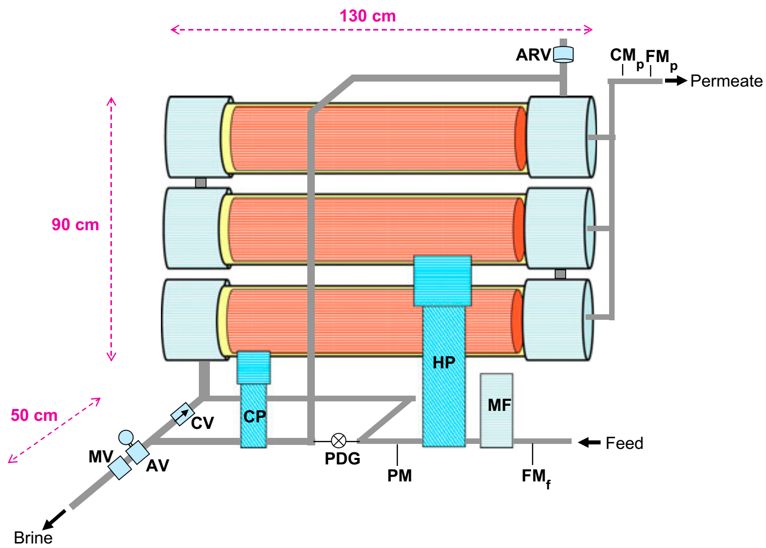

Fig. 2. A schematic design of a small compact BWRO-CCD unit with ME3 configuration comprising a single split module of 3 elements (8´´) for permeate production of 2.7 m^3/h at 25 lmh.

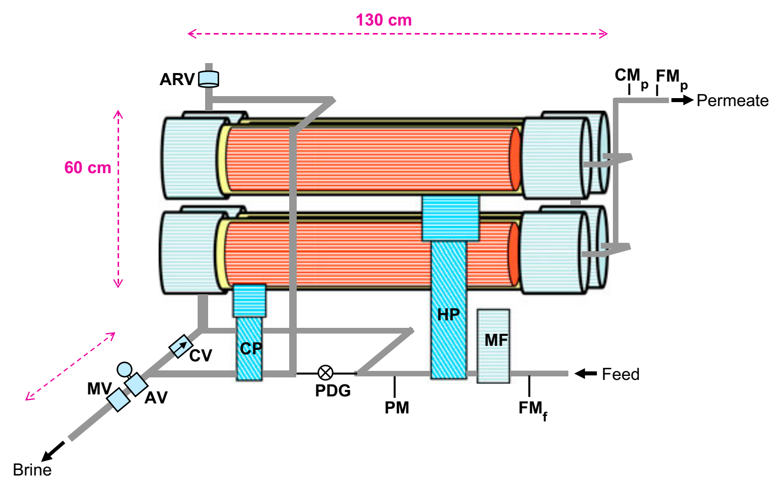

Fig. 3. A schematic design of a small compact BWRO-CCD unit with 2ME2 configuration comprising two split modules each of 2 elements (8´´) for permeate production of 3.8 m^3/h at 25 lmh.

consumption under reduced scaling and bio-fouling characteristics. The small compact design of said units and their high-recovery, low-energy demand and reduced fouling characteristics rest on the principles of the new CCD technology whereby recovery is a function of concentrate recycling irrespective of the number of elements per module with low-energy demand during the recycling stage being just above the theoretical energy.

The reduced scaling of the CCD technology arises from the dilution effect of recycled concentrate with fresh feed at inlet to module(s) combined with the consecutive sequential nature of the process whereby initiation of scaling can only occur toward the very end of each sequence when the recycled concentrate salinity reaches maximum and if scaling seeds start to appear at this stage they are immediately removed during the brine replacement by fresh feed at the desired recovery level. Bio-fouling in CCD is inhibited due to the large sequential salinity variations of the recycled concentrate which create unfavorable conditions for bacteria growth. Moreover, the cross flow in CCD can be controlled to a desired level independent of the pressurized feed flow; thereby, allow further reduction of scaling and fouling characteristics by process optimization.

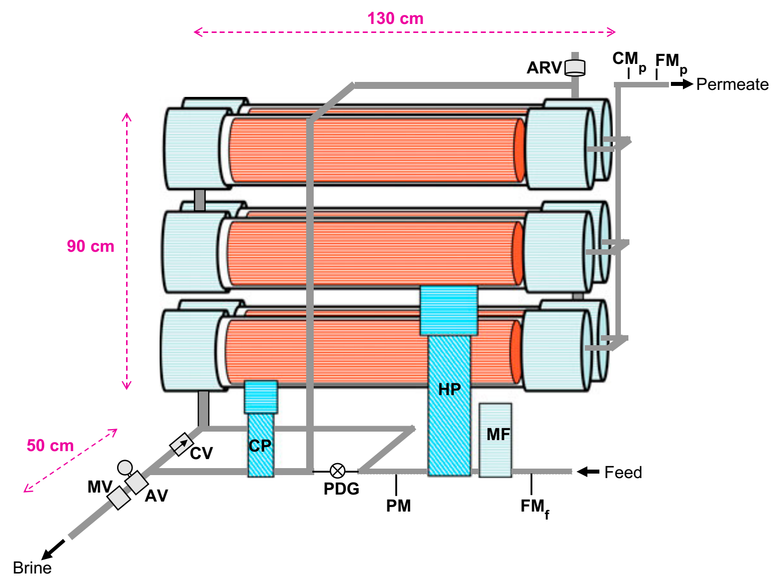

Fig. 4. A schematic design of a small compact BWRO-CCD unit with 2ME3 configuration comprising two split modules each of 3 elements (8´´) for permeate production of 5.4 m^3/h at 25 lmh.

The dimensions of small compact units displayed in Figs. 1–4 manifest the size of their components and in this regards the length of ~150 cm is dictated by the single-element pressure vessels, the height by HP and the width by the diameter of the pressure vessels and ground space requirements of the pumps (HP and CP), valves (AV, MV, and CV) and monitoring means (PDG, PM_f). The principle control features of simple small compact units relate to a fixed flow set-point of pressurized feed delivery under variable pressure conditions by HP-*vfd* through FM_f, initiation of PFD by AV opening at a defined PM pressure set-point and the resumption of CCD by AV closure when FMf volume count reach the desired set-point for complete brine replacement by fresh feed. The PFD sequential step of brine replacement by fresh proceeds under a relatively low applied pressure determined by the setting of the MV with an enhanced HP-*vfd* flow rate according to second HP-*vfd* set-point while power to CP is stopped. After completion of brine replacement by fresh feed, the resumption of CCD proceeds by the restoration of power to CP and the first flow set-point of HP-*vfd*. The control board of the simplest forms of small compact units relates to FM_f, FM_p, PM, CM_p, monitored energy and the operational set-points of flow ($Q_{HP\text{-}CCD}$, $Q_{HP\text{-}PFD}$), PFD feed volume and maximum sequential pressure or maximum sequential electric conductivity of recycled concentrate. Module pressure difference (Δp) in simplest form units is provided by PDG, and conductivities of feed water, recycled concentrate and brine could be determined manually when desired through sampling valves. It should be pointed out that simplest forms of compact units with uncontrolled CP of full power mode are intended for a predefined marrow flux range of operation and that increased flux range flexibility of such units requires controlled CP by *vfd* through flow meter means of recycled concentrate. Supply of antiscaling agent to the compact units, if required, will be provided by means of an externally located autonomously operated dosing pump and a delivery line to the feed inlet of units. The estimated dimensions and production capacity several small compact BWRO-CCD units of the designs displayed in Figs. 1–4 are provided in Table 1.

3. Typical performance of small compact BWRO-CCD units

The simulated performance of a small compact ME2 unit of the type described in Fig. 1 at 25 lmh (25˚C) with feed of 750 ppm NaCl using common membrane elements, such as ESPA1 or alike, is displayed in Table 2; wherein, columns are labeled 1–20 at the bottom. The indicated NaCl feed salinity manifests common feed sources of 800-900 ppm. The top data in Table 2 provides basic information related to elements, module type, and desired set-points of operation.

In the example under review, the test-conditions data of the selected element provide both **A** and **B** coefficients, the split module (8´´) design of ME2 corresponds to a combined length of 260 cm (=2 × 130)

Table 1
Compact BWRO-CCD units for upgrade of water supplies (<1,500 ppm) with high-recovery (>90%) and low-energy consumption of reduced scaling and bio-fouling characteristics for general industrial, agricultural, and domestic applications

CCD unit design configuration	Element diameter inch (cm)	Permeate production L/h	Permeate production m^3/day	Dimensions width-length-height cm	Unit typical features
ME2	4(10)	420	10.1	45 × 150 × 110	Fig. 1 (4´´)
ME3	4(10)	580	13.9	45 × 150 × 110	Fig. 2 (4´´)
2ME2	4(10)	840	20.2	55 × 150 × 110	Fig. 3 (4´´)
2ME3	4(10)	1,160	27.8	55 × 150 × 110	Fig. 4 (4´´)
ME2	8(20)	1,900	45.6	60 × 150 × 130	Fig. 1 (8´´)
ME3	8(20)	2,700	64.8	60 × 150 × 130	Fig. 2 (8´´)
2ME2	8(20)	3,800	91.2	80 × 150 × 130	Fig. 3 (8´´)
2ME3	8(20)	5,400	129.6	80 × 150 × 130	Fig. 4 (8´´)

with free closed circuit volume of 54.2 liter/module assuming an element volume of 15 liter, and the sequential operational set-points for the CCD step of fixed flux (=25 lmh) and module recovery (MR = 25%) and for the PFD step of MR (=25%), fixed feed flow by HP greater by 40% compared with CCD and feed source salinity (0.075%).

The entire data in Table 2 is generated theoretically using the basic information on top of the table and conventional expressions including RO and power equations with explanations provided hereinafter according to the labeled columns in the bottom of the table. The mode in the sequence is cited in column 1 and the step in the process provided in column 2 wherein 0 stands for PFD and numbers for sequential CCD cycles. The module inlet and outlet concentrations (%) are outlined in columns 3 and 4, respectively, with module inlet concentration during CCD accounting for the dilution effect due to mixing of recycled concentrate with fresh feed. The cumulative sequential periods (minute) of PFD and of CCD are provided in column 5 on the basis of the relevant fixed terms (min/step for PFD and min/cycle for CCD) found on top of the table as appropriate.

The applied pressure (bar) of PFD and the sequentially applied pressures (bar) during CCD cycles in column 6 of Table 1 are derived from expression (1); wherein, μ stands for flux, **A** for permeability coefficient, T_{CF} for temperature correction factor, $\Delta\pi_{av}$ for average concentrate side osmotic pressure difference, Δp for module inlet/outlet pressure difference, p_p for permeate release pressure, and π_p for average permeate-side osmotic pressure. The mean CCD sequential pressure in column 7 is based on the pressure data provided in column 6. The power requirements (kW) of the HP, CP, and HP + CP pumps are listed in columns 8, 10, and 11, respectively, and the specific energy (kWh/m^3) requirements of HP during the PFD step and the mean during the sequential CCD cycles on the basis of the mean applied pressure are provided in column 9. The power and specific energy terms are derived from the conventional expressions (2) and (3), respectively, wherein, P (kW) stands for power, Q_f (m^3/h) for flow rate of pressurized feed, Q_p (m^3/h) for flow rate of permeate, p (bar) for pressure and *eff* for the efficiency factor of the pump. The cumulative sequential time (minute) in column 12 is the sum of PFD and CCD. Permeate volumes (m^3) produced during the PFD step and the CCD cycles are provided in column 13, their sequential accumulations (Σm^3) in column 14 which together with the fixed closed circuit intrinsic volume (54.2 liter) provide the sequential recovery data in column 15 according to the expression (4); wherein, ΣV_p stands for the cumulative sequential permeate volume and V (=54.2 liter) for the intrinsic closed circuit volume. The cumulative sequential energy (ΣkWh) consumption over a defined sequential time interval is provided in column 16, and this information combined with the relevant cumulative permeate volume produced over the same time interval in column 14 (Σm^3) leads to the average sequential specific energy terms in column 17 according to the expression $\Sigma kWh/\Sigma m^3/h$. The mean permeate production flow rates (m^3/h) during the sequential progression which take account of the relative contributions of the PFD step and the CCD cycles of the process are provided in column 18. The salt content (ppm TDS) of produced permeates per PFD step and CCD cycles are provided in column 19 and their mean sequential value in column 20. The permeate salt content data in column 19 are derived from the fundamental RO expression (5); wherein, **B** stands for

Table 2
High-recovery low-energy simulated performance of a small compact BWRO-CCD ME2 unit with ESPA1(8´´) like elements and feed source of 750 ppm NaCl under MR = 25% (25°C) and CCD flux of 25 lmh

TEST - ESPA1
37.1 m2/Element
45.4 m3/day
1,500 ppm NaCl
10.5 bar Applied Pressure
15 % Recovery
25 Centig.
99.3 % Salt Rejection
9.285 bar NDP
50.988 l/m2/h Flux
5.4915 l/m2/h/bar -A
0.2803 l/m2/h - B

π(bar)-C(%)
750 ppm NaCl Feed
0.60 bar Osmotic Pressure
8.00 π(bar)/C(%)

UNIT DESIGN
1 Modules
2 Elements/Module
260 cm long PV
20 cm diameter PV
15 liter element volume
5 % lines volume
54.2 liter per module
54.2 liter per design

Pumps
0.75 HP *eff*.
0.75 CP *eff*.

Temperature
25 °C
1.000 TCF

PFD-ME2
0.075 % NaCl Feed
40 % increased HP flow
2.60 m3/h Feed
25 % Recovery
0.94 psi Δp 0.06 bar Δp
0.65 m3/h Permeate 8.8 lmh flux
1.95 m3/h Brine 0.100 % Brine
1.6703 min/step PFD
0.01807 m3/step Permeate
2.3 bar Applied Pressure
0.134 av-MR/Element-PFD
1.167 av-pf - PFD

CCD-ME2
0.10 % Initial feed
25.0 lmh Flux
25 % Module Recovery
0.38 bar Δp
5.6 psi Δp
1.86 m3/h Permeate (=Q_{HP})
5.57 m^3/h Qcp
0.58 min/cycle CCD
0.134 av-MR/Element-CCD
1.149 av-pf - CCD

SUMMARY: 90.0% Recovery (PDF+CCD)
42 m3/day
1.74 m3/h
0.334 kWh/m3
50 ppm
16.9 minute/Sequence
2.3 bar PFD
5.7 bar CCD minimum
10.1 bar CCD maximum

ME2 MODULE DATA				CCD Cycles & PFD Step							Combined Sequence (CCD Cycles & PFD Step)						PERMEATE		
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP	HP+CP	Time	Permeate - m3		REC	Energy		mean	Step	mean
Mode	Step	%	%	min	bar	mean	kW	kWh/m3	kW	kW	Σmin	m3/step	Σm3	%	ΣkWh	kWh/m3	m3/h	ppm	ppm
PFD	**0**	**0.08**	**0.10**	**1.67**	**2.3**	**2.3**	**0.224**	**0.345**	**0.000**	**0.224**	**1.7**	**0.018**	**0.018**	**25.0**	**0.006**	**0.345**	**0.65**	**33**	**33**
CCD	1	0.10	0.13	0.58	5.7	5.7	0.390	0.210	0.079	0.469	2.3	0.018	0.036	40.0	0.011	0.299	0.96	15	24
CCD	2	0.12	0.16	1.17	5.9	5.8	0.402	0.214	0.079	0.481	2.8	0.018	0.054	50.0	0.015	0.286	1.15	18	22
CCD	3	0.14	0.18	1.75	6.0	5.9	0.414	0.217	0.079	0.493	3.4	0.018	0.072	57.1	0.020	0.281	1.27	21	22
CCD	4	0.16	0.21	2.34	6.2	5.9	0.426	0.220	0.079	0.505	4.0	0.018	0.090	62.5	0.025	0.279	1.35	23	22
CCD	5	0.18	0.23	2.92	6.4	6.0	0.438	0.223	0.079	0.518	4.6	0.018	0.108	66.7	0.030	0.279	1.42	26	23
CCD	6	0.19	0.26	3.51	6.6	6.1	0.450	0.227	0.079	0.530	5.2	0.018	0.127	70.0	0.035	0.280	1.47	29	24
CCD	7	0.21	0.28	4.09	6.7	6.2	0.462	0.230	0.079	0.542	5.8	0.018	0.145	72.7	0.041	0.282	1.51	32	25
CCD	8	0.23	0.31	4.68	6.9	6.3	0.474	0.233	0.079	0.554	6.3	0.018	0.163	75.0	0.046	0.283	1.54	35	26
CCD	9	0.25	0.33	5.26	7.1	6.4	0.486	0.236	0.079	0.566	6.9	0.018	0.181	76.9	0.052	0.286	1.56	38	27
CCD	10	0.27	0.36	5.85	7.3	6.5	0.498	0.239	0.079	0.578	7.5	0.018	0.199	78.6	0.057	0.288	1.59	40	28
CCD	11	0.29	0.38	6.43	7.4	6.6	0.510	0.243	0.079	0.590	8.1	0.018	0.217	80.0	0.063	0.290	1.61	43	29
CCD	12	0.31	0.41	7.02	7.6	6.6	0.522	0.246	0.079	0.602	8.7	0.018	0.235	81.3	0.069	0.293	1.62	46	31
CCD	13	0.33	0.43	7.60	7.8	6.7	0.534	0.249	0.079	0.614	9.3	0.018	0.253	82.4	0.075	0.296	1.64	49	32
CCD	14	0.34	0.46	8.18	8.0	6.8	0.546	0.252	0.079	0.626	9.9	0.018	0.271	83.3	0.081	0.298	1.65	52	33
CCD	15	0.36	0.48	8.77	8.1	6.9	0.558	0.256	0.079	0.638	10.4	0.018	0.289	84.2	0.087	0.301	1.66	54	35
CCD	16	0.38	0.51	9.35	8.3	7.0	0.570	0.259	0.079	0.650	11.0	0.018	0.307	85.0	0.093	0.304	1.67	57	36
CCD	17	0.40	0.53	9.94	8.5	7.1	0.582	0.262	0.079	0.662	11.6	0.018	0.325	85.7	0.100	0.307	1.68	60	37
CCD	18	0.42	0.56	10.52	8.7	7.2	0.595	0.265	0.079	0.674	12.2	0.018	0.343	86.4	0.106	0.310	1.69	63	39
CCD	19	0.44	0.58	11.11	8.8	7.3	0.607	0.269	0.079	0.686	12.8	0.018	0.361	87.0	0.113	0.313	1.70	66	40
CCD	20	0.46	0.61	11.69	9.0	7.3	0.619	0.272	0.079	0.698	13.4	0.018	0.380	87.5	0.120	0.316	1.70	69	41
CCD	21	0.47	0.63	12.28	9.2	7.4	0.631	0.275	0.079	0.710	13.9	0.018	0.398	88.0	0.127	0.319	1.71	71	43
CCD	22	0.49	0.66	12.86	9.4	7.5	0.643	0.278	0.079	0.722	14.5	0.018	0.416	88.5	0.134	0.322	1.72	74	44
CCD	23	0.51	0.68	13.45	9.5	7.6	0.655	0.282	0.079	0.734	15.1	0.018	0.434	88.9	0.141	0.325	1.72	77	45
CCD	24	0.53	0.71	14.03	9.7	7.7	0.667	0.285	0.079	0.746	15.7	0.018	0.452	89.3	0.148	0.328	1.73	80	47
CCD	25	0.55	0.73	14.62	9.9	7.8	0.679	0.288	0.079	0.758	16.3	0.018	0.470	89.7	0.156	0.331	1.73	83	48
CCD	26	0.57	0.76	15.20	10.1	7.9	0.691	0.291	0.079	0.770	16.9	0.018	0.488	90.0	0.163	0.334	1.74	85	50
CCD	27	0.59	0.78	15.78	10.2	8.0	0.703	0.295	0.079	0.782	17.5	0.018	0.506	90.3	0.171	0.338	1.74	88	51
CCD	28	0.61	0.81	16.37	10.4	8.0	0.715	0.298	0.079	0.794	18.0	0.018	0.524	90.6	0.179	0.341	1.74	91	52
CCD	29	0.62	0.83	16.95	10.6	8.1	0.727	0.301	0.079	0.806	18.6	0.018	0.542	90.9	0.186	0.344	1.75	94	54
CCD	30	0.64	0.86	17.54	10.8	8.2	0.739	0.304	0.079	0.818	19.2	0.018	0.560	91.2	0.194	0.347	1.75	97	55
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

the diffusion coefficient, C_f for the feed concentration and pf_{av} for the average concentration polarization factor. The average concentration polarization factor is derived by expression (6); wherein Y_{av} stands for the average element recovery expressed by (7) with MR being the MR (%) and n the number of elements per module. The exponent empirical coefficient (0.45) in (6) was derived from the beta terms of an IMS Design program for an ME2 system with ESPA1 element under the exact same conditions as specified in Table 2. The mean permeate salt content during the sequential progression in column 20 takes account of the relative contributions of the PFD step and CCD cycles in the process.

The concentrate-side pressure drop (Δp) in RO modules manifests flow-induced pressure losses as function of the number of elements and their internal design with increased packing of declined free space and enhance flow restrictions effecting larger Δp and vice versa. The expression for Δp takes account of flow rates at module inlet (Q_{mi}) and outlet (Q_{mo}), the number of elements (n) and their packing characteristics as expressed by a typical empirical coefficient. The values of Δp in Table 2 are derived from expression (8) that gives results similar to those from the IMS Design program. Noteworthy according to (8) is the expected decline in Δp with increased MR. The MR recovery in CCD is defined by expression (9) from module inlet (Q_{mi}) and outlet (Q_{mo}) flow rates and the difference between them which manifest the flow rate of permeate. The Q_{mi} flow rate in (9) may be expressed in terms of Q_{HP} and Q_{CP} according to (10), since under CCD operational conditions $Q_{HP} = Q_p$ and $Q_{mo} = Q_{CP}$. Strict module performance control of CCD requires operation with fixed MR and according to (9) this may be possible only if each of the Q_{HP} and Q_{CP} flow rates is kept constant. Strict control of Q_{HP} and Q_{CP} requires *vfd* controlled HP and CP pumps through flow monitoring means.

$$p_{appl} = \mu/A/T_{CF} + \Delta\pi_{av} + \Delta p/2 + p_p - \pi_p \quad (1)$$

$$P = Q_f \times p/36/eff \quad (2)$$

$$\text{Specific energy } = P/Q_p = (Q_f/Qp) \times p/36/eff \quad (3)$$

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

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

$$pf_{av} = 10^{(\mathbf{0.45 \times Yav})} \quad (6)$$

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

$$\begin{aligned}\Delta p(\text{bar}) &= (8^*10^{-3}) \times n \times [(Q_{mi} + Q_{mo})/2]^{1.7} \\ &= (8^*10^{-3}) \times n \\ &\quad \times [(Q_{mi}/2 \times (2 - \text{MR}/100)]^{1.7}) \end{aligned} \quad (8)$$

$$\begin{aligned}\text{Module recovery(MR)} &= (Q_{mi} - Q_{mo})/Q_{mi} \times 100 \\ &= Q_p/(Q_p + Q_{CP}) \times 100 \\ &= Q_{HP}/(Q_{HP} + Q_{CP}) \times 100 \end{aligned} \quad (9)$$

$$Q_{mi} = Q_{HP} + Q_{CP} = Q_p + Q_{CP} \quad (10)$$

The theoretical simulation results of high recovery and low energy in Table 2 of a small compact BWRO-CCD ME2 unit with feed of 750 ppm NaCl operated at 25 lmh with MR = 25% are displayed graphically in Figs. 5–10. The relationships between time, CCD cycles and recovery during the sequential progression described in Table 2 are displayed in Fig. 5 with linear relationship revealed between time and CCD cycles [A], and exponential relationships between time and recovery [B] as well as between CCD cycles and recovery [C]. The findings manifest cycles of fixed time duration and an exponentially increase number of CCD cycles as function of increased sequential recovery. The applied pressure demand of the process under review is displayed in Fig. 6 as function of CCD cycles [A] and recovery [B] and the noteworthy features revealed are the fixed low-pressure requirement during the PFD step of brine replacement with fresh feed and the gradual increase of CCD applied pressure with increased recovery with mean applied pressure ($p_{app\text{-}m}$) manifesting the mean specific energy of HP ($p_{app\text{-}m}/36/\text{eff}$) at each particular point along the exponential increased pressure diagonal (Fig. 6(B)).

The low-energy requirement of CCD manifests the mean pressure of a fixed flow variable pressure sequential process under conditions that are unattainable by conventional BWRO. The actual power demand of pumps (HP and CP) during process under review in Table 2 is displayed in Fig. 7 as function of CCD cycles [A] and recovery [B] and the results reveal as expected increased power demand as function of consecutive sequential progression under fixed flow and variable pressure conditions. The same trend revealed for pressure (Fig. 6) and power (Fig. 7) is also revealed for specific energy in Fig. 8 as function of sequential CCD cycles [A] and recovery [B] that explains the low specific energy in such a process even at high recovery. The absolute and mean permeate salinity (TDS-ppm NaCl) as function of sequential progression during the process under review are displayed in Fig. 9 as function of CCD cycles [A] and recovery [B], and these results are said for CCD flux of 25 lmh with MR = 25% and average concentration polarization factor of 1.149 at 25˚C. Most obviously, operating at higher flux shall result in increased quality of permeates and vice versa.

In contrast with convention techniques which in order to achieve > 90% recovery require staged pressure vessels of long line of membrane elements (~18), recovery in BWRO-CCD proceed as function of sequential recycling on time scale irrespective of the number of lined elements. The attainment of 90% recovery in the small compact ME2 design under

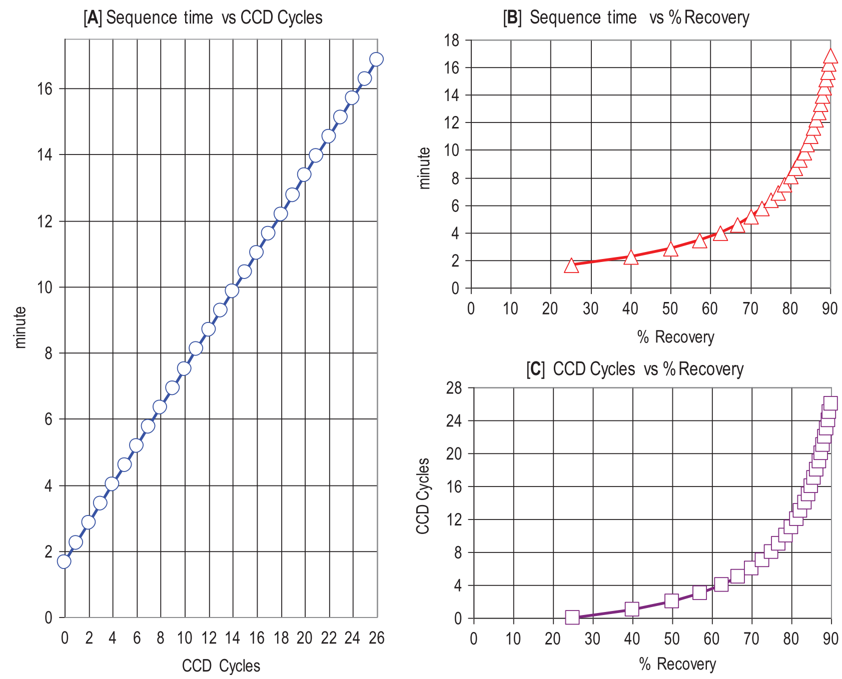

Fig. 5. Relationships between sequence time and CCD cycles (A), sequence time and recovery (B) and CCD cycles and recovery (C) during the high-recovery, low-energy BWRO-CCD ME2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

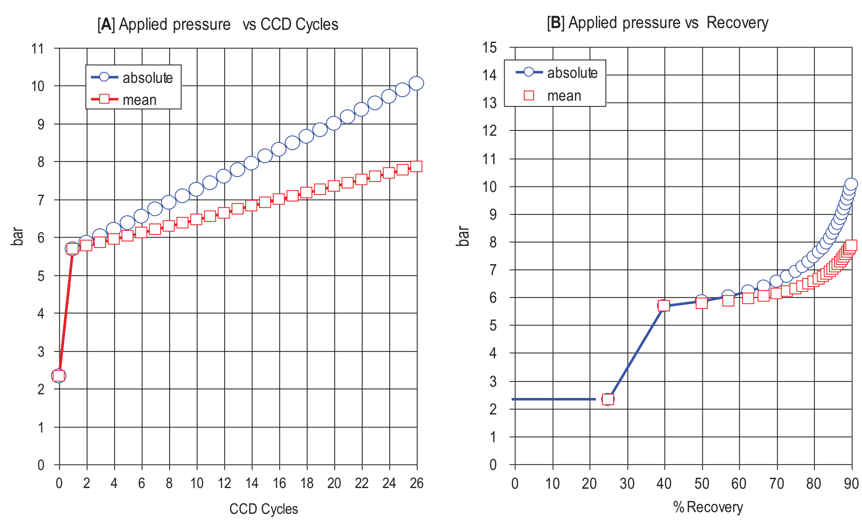

Fig. 6. Applied pressures as function of CCD cycles (A) and recovery (B) during the high-recovery low-energy BWRO-CCD NE2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

review in Table 2 requires a sequence time of 16.9 min of 26 CCD cycles with the specific energy (absolute and mean) and permeate salinity (absolute and mean) during the sequence progression illustrated in Fig. 10(A) and (B), respectively. The 16.9-min sequence time period for 90% recovery in the system under review is divided into a PFD step of 1.7 min experienced 10% of the sequential period and 26 CCD cycles during 15.2 min experienced 90% of the sequential period. The mean value data revealed in Fig. 10(A) and (B) are the cumulative average during the sequential progression accounting for both the PFD step and CCD cycles. The attainment of 90% recovery in the ME2 design under review is achieved

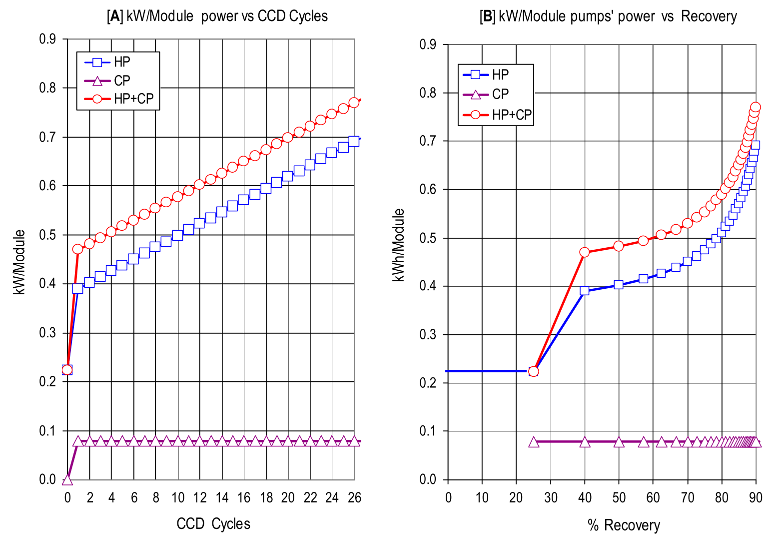

Fig. 7. Power demand as function of CCD cycles (A) and recovery (B) during the high-recovery low-energy BWRO-CCD ME2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

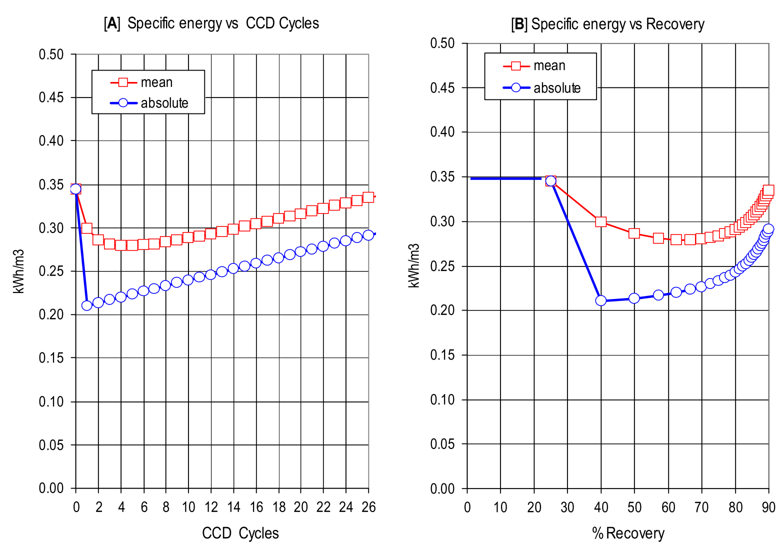

Fig. 8. Specific energy as function of CCD cycles (A) and recovery (B) during the high-recovery low-energy BWRO-CCD ME2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

by a CCD set-point of 9.9 bar maximum sequential pressure at which point the system will revert to perform brine replacement by pressurized feed at 2.3 bar with 25% recovery until the replaced volume is equivalent to the intrinsic free volume of the closed circuit (54.2 liter) and thereafter CCD shall be resumed. Noteworthy in Fig. 10(A) is the relatively small contribution of the PFD step to the specific energy of the entire process which amount to ~0.05 kWh/m^3 above the near absolute energy conversion efficiency of CCD (~0.30 kWh/m^3) at 90% recovery. Another noteworthy feature in Fig. 10(B) is the relatively small PFD contribution with flux of 8.8 lmh to the overall salinity of the average permeates at 90% recovery.

4. Types of small compact BWRO-CCD units

Small compact BWRO units are widely used worldwide for diverse applications of different types and requirements, and in this context, several different types of small compact BRWO-CCD units are considered below.

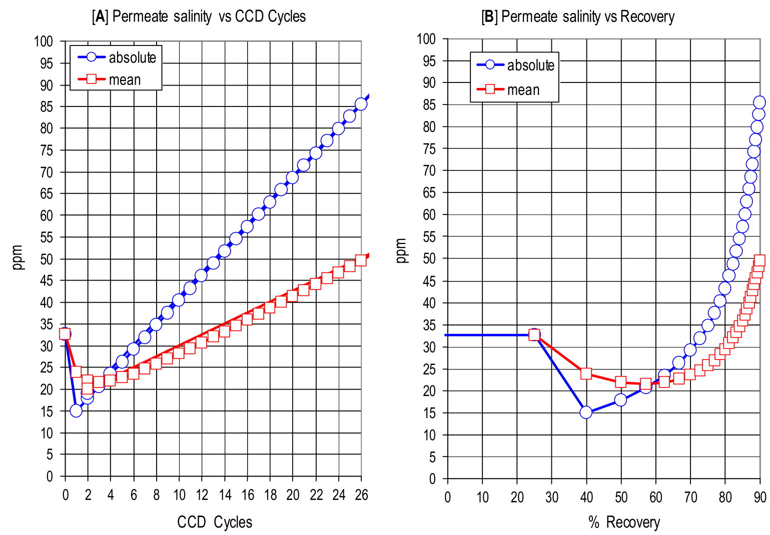

Fig. 9. Permeate salinity as function of CCD cycles (A) and recovery (B) during the high-recovery low-energy BWRO-CCD ME2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

4.1. Small compact BWRO-CCD units with PVC lines and uncontrolled CP

The use BWRO for upgrade of water supplies requires on many occasions inexpensive small compact units as example for intensive "green-house" irrigation, domestic use, and diverse industrial applications wherein permeate quality is not crucial and defined by a certain maximum TDS level. Such small inexpensive units should operate with high recovery and low energy in order to enable their cost-effective operation also where raw water supplies and energy expenses are high. Small compact BWRO-CCD units of very small footprints for upgrade of water supplies made of plastic pressure vessels and lines of 15 bar pressure rating with an uncontrolled CP of fixed power operation meet the criteria requirements of low installation costs combined with high-recovery and low-energy performance characteristics. In order to enable the use of an uncontrolled CP of fixed power in such units, they should be designed to operate at a single fixed CCD flux under variable pressure conditions of small MR variability as function small

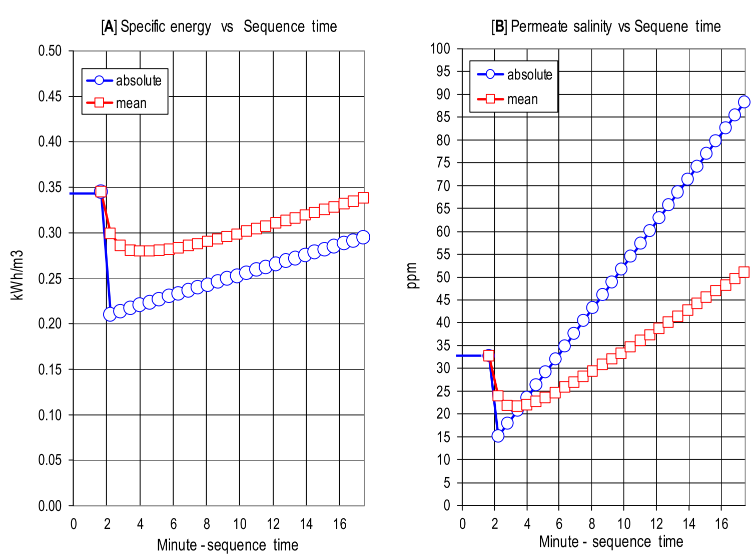

Fig. 10. Sequential time variations of specific energy (A) and permeate salinity (B) during the high-recovery low-energy BWRO-CCD ME2 simulation of 750 ppm NaCl feed at 25 lmh with MR = 25% described in Table 2.

Table 3
Fixed CCD HP flux (25 lmh) operation of the ME2 design displayed in Table 2 with CP actuated without flow control at fixed power (0.082 kW) and the relationship of Δp to Q_{CP}, MR, Y_{av}, and pf_{av}

HP (m^3/h)	Flux (lmh)	CP (m^3/h)	MR (%)	Δp (bar)	CP (kW)	Y_{av} (ratio)	*beta* (pf_{av})
1.86	25.1	7.42	20.0	0.30	0.082	0.106	1.116
1.86	25.1	6.96	21.1	0.32	0.082	0.112	1.123
1.86	25.1	6.55	22.1	0.34	0.082	0.118	1.130
1.86	25.1	6.18	23.1	0.36	0.082	0.123	1.136
1.86	*25.1*	*5.86*	*24.1*	*0.38*	*0.082*	*0.129*	*1.143*
1.86	25.1	5.57	25.1	0.40	0.082	0.134	1.149
1.86	25.1	5.30	26.0	0.42	0.082	0.140	1.156
1.86	25.1	5.06	26.9	0.44	0.082	0.145	1.162
1.86	25.1	4.84	27.8	0.46	0.082	0.150	1.168
1.86	25.1	4.64	28.6	0.48	0.082	0.155	1.174
1.86	25.1	4.45	29.5	0.50	0.082	0.160	1.181
1.86	25.1	4.28	30.3	0.52	0.082	0.165	1.187
1.86	25.1	4.12	31.1	0.54	0.082	0.170	1.192
1.86	25.1	3.98	31.9	0.56	0.082	0.175	1.198
1.86	25.1	3.84	32.6	0.58	0.082	0.179	1.204

Δp, or alternatively, by the control of Q_{CP} and MR through flux adjustment, and these aspects are discussed next.

Operation of ME2 with fixed flux ($Q_{HP} = 1.86\ m^3/h$–25 lmh) as exemplified in Table 2 with uncontrolled CP of fixed power (0.082 kW) in the Δp range 0.30–0.58 bar induces the variations of Q_{CP}, pf_{av} (**6**), Y_{av} (**7**) and MR (**9**) outlined in Table 3 with relationship of Δp to flow rates (HP and CP), MR and pf_{av} displayed graphically in Fig. 11(A)-(C), respectively. The red line in the Table 3 stands for the fully controlled operation described in Table 2. The theoretically data furnished in the table under review implies that a fixed power (0.082 kW) CP selection of $7.42\ m^3/h$ at $\Delta p = 0.30$ bar will deliver $5.57\ m^3/h$ at $\Delta p = 0.40$ and with increased Δp in the range of 0.40–0.56 bar (40% increase) will effect the respective change of $5.57–3.98\ m^3/h$ in flow rate of CP, 25–31.9% in MR, 13.4–17.5% in average element recovery (Y_{av}), and 1.149–1.198 in average beta (pf_{av}). The theoretical results in Table 3 imply that operation with fixed flux (25 lmh) and uncontrolled CP of a desired fixed power selection (0.082 kW) will enable a sufficiently effective CCD process of 90% recovery with subsequent rise of Δp to 0.56 bar causing decreased circulation flow to $3.98\ m^3/h$, increased MR to 31.9%, increased average element recovery to 17.5% and increased beta to 1.198 a value still under the recommended maximum of 1.20 by the IMS Design program for the ESPA1 elements. The subsequent rise in Δp will not affect the energy consumption or the recovery of the system; however, the quality of permeates will decrease as function of increased pf_{av} according to (5).

A different approach to achieve a near constant pressure ($\Delta p = 0.384 \pm 0.014$ bar) operation of a fixed flow ($5.57\ m^3/h$) and power (0.082 kW) CP without need of *vfd* is described in Table 4 by means of induced HP-*vfd* flow variations in the range 2.10–1.55 m^3/h (28.3–20.9 lmh) which effect the respective

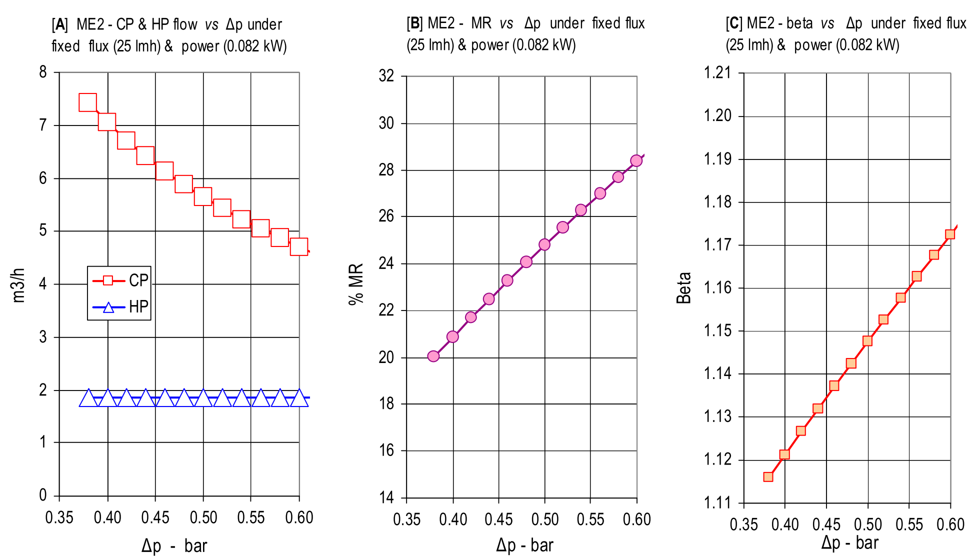

Fig. 11. The relationships of Δp to flow rates (HP and CP) (A), module recovery (B), and beta (C) during the fixed flux (25 lmh) operation of the ME2 design displayed in Table 2 with CP actuation at fixed power (0.082 kW) without flow control means according to the data furnished in Table 3.

Table 4
Constant CP flow (5.57 m^3/h) with fixed power (0.082 kW) operation of the ME2 design displayed in Table 2 by adjustments of HP-*vdf* flow rates (Q_{HP}) in order to maintain a desired Δp and satisfactory values of MR, Y_{av}, and pf_{av}

HP (m^3/h)	Flux (lmh)	CP (m^3/h)	MR (%)	Δp (bar)	CP (kW)	Y_{av} (ratio)	*beta* (pf_{av})
2.10	28.3	5.57	27.4	0.398	0.082	0.148	1.166
2.05	27.6	5.57	26.9	0.395	0.082	0.145	1.162
2.00	27.0	5.57	26.4	0.393	0.082	0.142	1.159
1.95	26.3	5.57	25.9	0.390	0.082	0.139	1.155
1.90	25.6	5.57	25.4	0.388	0.082	0.136	1.152
1.85	*24.9*	*5.57*	*24.9*	*0.385*	*0.082*	*0.134*	*1.148*
1.80	24.3	5.57	24.4	0.383	0.082	0.131	1.145
1.75	23.6	5.57	23.9	0.380	0.082	0.128	1.141
1.70	22.9	5.57	23.4	0.378	0.082	0.125	1.138
1.65	22.2	5.57	22.9	0.375	0.082	0.122	1.134
1.60	21.6	5.57	22.3	0.373	0.082	0.119	1.131
1.55	20.9	5.57	21.8	0.370	0.082	0.116	1.127

changes in MR (27.4–21.8%), average element recovery (Y_{av}: 14.8–11.6%) and average beta (pf_{av}: 1.166–1.127). The relationships of Δp to flow rates (HP and CP), MR and pf_{av} are presented graphically in Fig. 12(A)–(C), respectively. The aforementioned approach implies the ability the sustain a near constant CP flow rate (5.57 m^3/h) and Δp (0.385 ± 0.015 bar) of CP with fixed power (0.082 kW) by means of HP-*vfd* flow control means. In this case, the near fixed flow of CP is achieved in response to Δp pressure variations, or in simple terms, when Δp is increased the flow rate of HP-*vfd* is decreased to the desired set-point level of Δp. Since Δp of membranes is gradually increased irreversibly as function of age irrespective of scaling effects; therefore, the disadvantage of this approach relates to the steady decrease in permeate production capacity with time. The flow rate control of CP through that of HP implies a periodic decrease of Q_{HP} as function of increased Δp and vice versa, since under ordinary conditions Δp should drop when scaling is removed by a successful CIP procedures. The best approach to sustain an uncontrolled CP operation in CCD is that revealed by the data in Table 3 provided that the beta is maintained below 1.20 with occasional adjustments of flux only when beta exceeds 1.20.

4.2. Small compact BWRO-CCD units with PVC lines and controlled CP

The small compact BWRO-CCD units under review in this section are for 15 bar maximum pressure rating and are made with PVC lines, or alike, and comprised of HP and CP with flow control means. The flow rate control means of both pumps independent of each other enable flexible CCD performance optimization of a specific source with respect to recovery, permeates quality, energy consumption, MR concentration polarization (beta) and other parameters. For instance, such units could be made to oper-

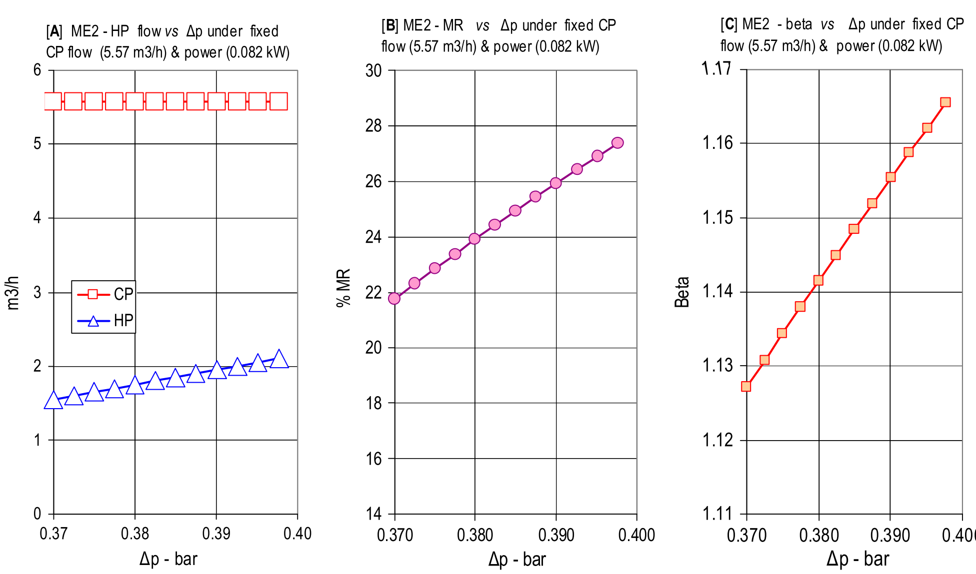

Fig. 12. The relationships of Δp to flow rates (HP and CP) (A), module recovery (B), and beta (C) during fixed flow CP (5.57 m^3/h) and power (0.082 kW) operation of the ME2 design displayed in Table 2 according to the data furnished in Table 4.

ate at a desired flux (HP control) with a desired cross flow (CP) and attain a desired recovery under the preferred MR and concentration polarization (*pf –beta*) conditions. Control of flux and *pf* imply control of permeate concentration (**5**) at desired recovery level. Control of MR through the set-points of Q_{HP} and Q_{CP} provides on line means for maximum recovery optimization before scaling is unavoidable. Simple small compact BWRO-CCD units of flexible performance control require the adding of *vfd* means to the CP and a flow meter means in the closed circuit and therefore are somewhat more expensive to install compared with equivalent units without CP control. Fully controlled units are better suited for an automated operation with or without remote control.

4.3. Small compact BWRO-CCD units of high-pressure rating (>15 bar)

Small compact BWRO-CCD could be made to operate with pressure rating up to 31 bar (~450 psi) by the appropriate selection of components which are exposed to pressure including HP, CP, conducing lines, and monitoring means. Accordingly, pressure lines should be made of stainless steel alloys (e.g. SS306, SS316, Super-Duplex and alike) with specific selection in compliance with the maximum salinity of the recycled concentrate. Small compact high-pressure BWRO-CCD units are intended for the desalination of feed sources of higher salinity compared with conventional water supplies (>1,000 ppm) such as brackish water and/or recycled industrial effluents wherefrom permeates of sufficient quality could be retrieved for further use. The high-pressure units in reference should comprise full control means of both pumps and sufficient monitoring means to enable an effective process control including *on line* performance optimization and fine tuning.

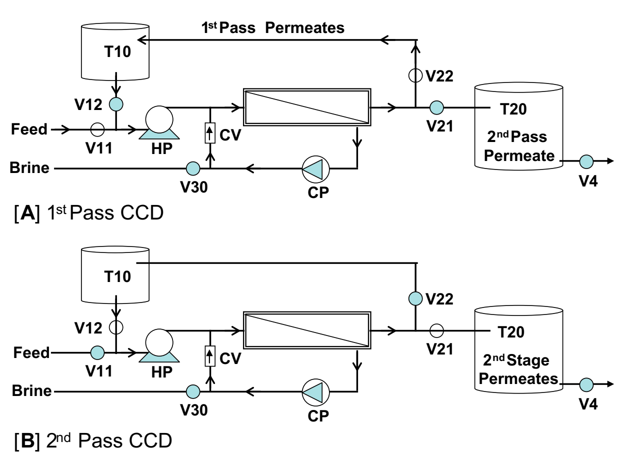

Fig. 13. A schematic design of a double-pass small compact BWRO-CCD unit for high-quality permeates showing the actuation modes of the 1st pass (A) and 2nd pass (B).

4.4. Small compact BWRO-CCD units of special requirements

Small compact units for desalination applications of special requirements are normally required by the pharmaceutical industry for the production of drugs, for medical dialysis in hospital and special centers everywhere worldwide, and by the solid-state electronic industry of semiconductors and electronic circuits that produce vital components for computers and control systems of appliances and for everything that moves on land, in water, under water, in air and in space. Requirements of special units may relate to choice of components and/or quality of permeate with units for the pharmaceutical industry and for medical dialysis normally characterized by high hygienic standards and those for the solid-state electronic industry by the ultra clean space operational requirements with strict control of permeate quality. Attainment of high hygienic standards and ultra clean space operational requirements of small compact units could be met by the proper choice of components such as for example certified stainless steel pressure vessels and lines for the production and delivery of permeates.

5. Small compact double-pass BWRO-CCD units

The small compact BWRO-CCD units considered hereinabove could be made to perform a two-pass process for high-quality permeates production of 80–85% overall recovery with production rate just under half that of a single-pass configuration. The making of a single-pass unit perform a double-pass process requires an intermediary storage tank wherein permeates of the 1st pass are stored and then used as feed in the 2nd pass process and the schematic design of such a system and its principle modes of operation is displayed in Fig. 13(A) and (B) and discussed hereinafter. The 1st pass described in Fig. 13(A) is that of the source with permeates of 1st pass collected in the intermediary tank (**T10**) and after the 1st pass reaches its predefined recovery (88–92%) the permeates of the 1st pass become the feed of the 2nd pass with final low salinity permeates collected in the **T20** reservoir. The entire two-pass process is performed continuously with 2nd pass in succession to 1st pass and with each pass separately controlled according to predefined set-points of operation with regards flux, cross flow, MR, recovery and the desired permeates quality selection on the basis of electric conductivity monitoring. The configuration of unit during the 1st pass operation is illustrated in Fig. 13(A) with the externally received feed and the valve means positions (V11-O and V12-C); wherein, the term "O" stands henceforth for an opened 2-way valve and "C" for a closed 2-way valve. During the 2nd pass operation, the external feed source is disconnected, and the internal feed source (T10) is activated as revealed by the actuated valve means positions (V11-C and V12-O) in Fig. 13(B). The initiation of the 2nd pass will take place by the maximum pressure set-point of the 1st pass and that of the 1st pass by the maximum pressure set-point of the 2nd pass. Permeates transfer to either T10 or T20 will proceed in response to the monitored electric conductivity (EC) of permeates received from the BWRO-CCD unit with permeates of EC above a predefined level collected in T10 (V21-C and V22-O) and those under said predefined EC level collected in T20 (V21-O and V22-C).

The volume of the intermediary tank (T10) in the design under review (Fig. 13) should manifest the flow rate of the 1st pass and the sequence time duration required to reach the desired recovery. For example, in a unit with 1st pass permeate production of 2.0 m^3/h and sequence duration of 15 min the theoretical volume of T10 should be 500 liter plus 25% spare which account for a total recommended volume of 600 L. The capacity of the final permeate product reservoir (T20) depends on the needs of the user. The tanks in the small compact BWRO-CCD units should be placed at a convenient location away from the unit cabinet with lines connecting to the cabinet, but with valves means included in the unit cabinet since managed by its control board.

The quality of permeates received by the double-pass unit design in Fig. 13 will depend on the choice of elements and the selected of operational conditions of each pass with respect to flux, recovery and module recovery which may be different. A double-pass of a small compact BWRO-CCD ME2 unit is illustrated in Table 5 with 350 ppm NaCl feed using ESPA1 like membranes elements of 99.3% salt rejection as well as with similar elements of 99.6% salt rejection. The results of both examples in Table 5 pertain to double-pass simulations with the same ME2 unit and two different types of elements distinguished from each other only with respect to salt rejection (99.3 and 99.6%)—the cited salt rejections are common of commercial membrane elements. Both double-pass simulations are performed under the exact same conditions of 90% recovery of 1st pass and 88.9% recovery of 2nd pass with the exact volume of permeate received in

Table 5
Simulated results of a single- and double-pass performance of a BWRO-CCD ME2 unit with two different type of elements, distinguished only by their salt rejection, using a feed source of 350 ppm TDS NaCl at inlet to 1st pass and permeate of 1st pass as feed of 2nd pass with 1st pass executed with 90% recovery and the combined double pass with 80% recovery

BWRO-CCD ME2	99.3% element rejection			99.6% element rejection		
Double-pass parameters	1st-Pass	2nd-Pass	1st+2nd	1st-Pass	2nd-Pass	1st+2nd
Feed (ppm)	350.0	23.1		350.0	13.2	
Membrane rejection (%)	99.3	99.3		99.6	99.6	
A coefficient (l/m^2/h/bar)	5.492	5.492		5.492	5.492	
B coefficient (l/m^2/h)	*0.280*	*0.280*		*0.160*	*0.160*	
CCD flux (lmh)	25.0	25.0		25.0	25.0	
CCD module recovery (%)	25.0	25.0		25.0	25.0	
Number CCD cycles	26	23		26	23	
PFD flux (lmh)	8.8	8.8		8.8	8.8	
PFD module recovery (%)	25.0	25.0		25.0	25.0	
Sequence recovery (%)	*90.0*	*88.9*	*80.0*	*90.0*	*88.9*	*80.0*
Sequence duration (min)	16.9	15.1	32.0	16.9	15.1	32.0
Mean permeate (ppm)	*23.10*	*1.528*	*1.528*	*13.23*	*0.426*	*0.426*
Σ(energy-consumption) (kWh)	0.132	0.097	0.229	0.133	0.096	0.229
Σ(feed volume) (liter)	542.2	488.0	542.2	542.2	488.0	542.2
Σ(permeate volume) (liter)	488.0	433.8	433.8	488.0	433.8	433.8
Permeate production per hour (m^3/h)	1.73	1.72	0.81	1.73	1.72	0.81
Permeate production per day (m^3/day)	41.6	41.4	19.5	41.6	41.4	19.5
Mean specific energy (kWh/m^3)	0.270	0.224	0.528	0.273	0.221	0.528

the 1st pass used as feed in the 2nd pass. The data furnished in Table 5 is for a unit of the schematic design displayed in Fig. 1 configured for a double-pass operation with added lines and tanks according to Fig. 13. The simulation results in Table 5 are derived by complete analogy with the comprehensive data analysis of Table 2.

The results in Table 5 for feed of 350 ppm NaCl exemplifies common supply sources of 375–400 ppm (750–800 μS/cm) which need to be upgraded in quality for further use by either a single-pass or double-pass processes. A single-pass application of the BWRO-CCD ME2 unit at 90% recovery yields permeates of 23.1 ppm TDS with membranes of 99.3% rejection, or of 13.2 ppm TDS with membranes of 99.6% rejection, in both cases with the same sequence duration (16.9 min), flow rate (1.73 m^3/h–41.6 m^3/day), and energy consumption (0.27 kWh/m^3). The results of a 2nd pass by the same unit, with permeates of 1st pass used as feed, under the exact same flow (flux) conditions as during the 1st pass are specified in Table 5 in the columns under the heading 2nd-pass, and the combined results of the double-pass specified in the columns under the heading 1st + 2nd. A double-pass application of the BWRO-CCD ME2 unit under review with an overall 80% recovery yields permeates of 1.53 ppm TDS with membranes of 99.3% rejection, or of 0.426 ppm TDS with membranes of 99.6% rejection, in both cases with the same combined sequences duration (32.0 min), flow rate (0.81 m^3/h–19.5 m^3/d), and energy consumption (0.528 kWh/m^3).

The exact same procedure as aforementioned with membranes of 99.3% rejection, if applies to a feed source of 200 ppm will afford 1st pass permeates of 13.2 ppm and 2nd pass permeates of 0.80 ppm with all other data being rather similar that of the relevant columns in Table 5. Likewise, the exact same procedure as aforementioned with membranes of 99.6% rejection if applies to a feed source of 200 ppm will afford 1st pass permeates of 7.56 ppm and 2nd pass permeates of 0.26 ppm with all other data being rather similar that of the relevant columns in Table 5.

Increased permeate production rate and quality both depend on flux with greater production rate of an improved quality product concomitant with increased flux and vice versa. For instance, the simulated double-pass results of the same system described in Table 5 with membranes of 99.6% rejection except for CCD flux of 35 lmh instead of 25 lmh reveals single-pass permeate of 9.45 ppm TDS at 90% recovery (0.379 kWh/m^3) over a sequence of 12.0 min and a double-pass process 22.8 min long of 80% recovery wherefrom permeates of 0.234 ppm TDS are received with 0.753 kWh/m^3. In simple terms, increase quality permeates is concomitant with increased flux and energy demand. Incidentally, the simulated results for feed of 200 instead of 350 ppm TDS under the same flux conditions (35 lmh of CCD) with membranes of 99.6% rejection reveal single-pass permeates of 5.4 ppm TDS with 90% recovery (0.356 kWh/m^3) and double-pass permeates of 0.13 ppm TDS received with 0.682 kWh/m^3 with 80% recovery.

6. Concluding remarks

The adaptation of the newly emerging the CCD technology to small compact is exemplified with the BWRO-CCD NMEn ($N = 1–2$; $n = 2–3$) units design for 500–5,500 l/h permeate production of single- or double-pass quality permeates for diverse applications. The small compact BWRO-CCD units described herein above are characterized by high-recovery, low-energy consumption without need of energy recovery, durable performance of reduced fouling and small footprints. The already demonstrated [3,7,10] ability of CCD to allow high recovery with low energy, considered in the context that such performance is attainable already at the level of a single-element module instead of the long line of elements (12–18) required by conventional techniques to achieve high recovery (90%), makes CCD an ideal technology for small compact units, unmatched by any conventional technique. Small compact BWRO-CCD units can be design in various configurations of high- or low-performance flexibility, made of PVC or stainless steel components and intended for ordinary, hygiene or clean environment applications.

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