Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.822628

52 (2014) 5717–5730
September

Taylor & Francis
Taylor & Francis Group

Closed circuit desalination series no. 8: record saving of RO energy by SWRO-CCD without need of energy recovery

Avi Efraty

Desalitech Ltd., P.O. Box 132, Har Adar, Israel 90836
Tel. +972 52 4765 687; Fax: +972 2 5700 262; email: avi@desalitech.com

Received 22 June 2012; Accepted 4 June 2013

ABSTRACT

A theoretical model is developed for comparing reverse osmosis (RO) energy and permeates quality of closed of circuit desalination (CCD) and conventional plug flew desalination (PFD) under the same conditions. The application of the theoretical model is illustrated by a comparison between a CCD unit with two modules each of four elements and a single module conventional PFD unit with eight elements in the context of ocean water (3.5%) desalination with 50% recovery at 25°C under average flux of 13 LMH and 85% efficiency of feed pressurizing pumps using the same membrane elements (SWC6). This model analysis reveals savings of RO energy by CCD compared with conventional PFD as function of its absolute energy conversion (AEC) efficiency (in bracket) as followed: 9.8% (95%), 13.4% (90%), 17.2% (85%), 20.6% (80%), 23.8% (75%), and 28.7% (70%). Most large and modern conventional seawater RO plants operate with AEC efficiency in the range of 70–80% and therefore, the actual RO energy saved by CCD compared with such conventional techniques is found in the respective range of 28.7–20.6%. Despite the large difference in RO energy revealed by the model analysis between the compared techniques, both produce about the same quality permeates. CCD is a continuously staged and pressure-boosted consecutive sequential technology which operates with near AEC efficiency without need for energy recovery (ER) from brine, and the low RO energy requirements by this technique manifest the average diagonal sequential pressure rise as function of increased sequential recovery under conditions of fixed flow rates of pressurized feed and permeate. According to the model analysis, CCD of ocean water (3.5%) at 13 LMH with 50% recovery proceeds with 1.625 kWh/m^3 compared with 1.962 kWh/m^3 by conventional techniques with AEC efficiency of 85%. The model analysis energy of 1.625 kWh/m^3 for ocean water (3.5%) CCD at 13 LMH with 50% recovery agrees with extrapolated energy for ocean water (1.60–1.70 kWh/m^3) from experimental results (2.0–2.1 kWh/m^3) received for the Mediterranean water (4.1%) under the same conditions. A pressure-volume work model for high pressure pump (HP) (85% *eff.*) in CCD revealed under infinitesimally small permeation of near zero flux conditions the theoretical minimum energies 1.40 and 1.25 kWh/m^3 for the Mediterranean (4.1%) and ocean (3.5%) water, respectively. Extrapolation of experimental CCD energies (HP + CP) to near zero flux revealed 1.44 and 1.29 kWh/m^3 for the Mediterranean and ocean water, respectively. The difference between the extrapolated (HP + CP) and theoretical minimum (HP) revealed the minor circulation pump (CP) energy contributions 0.04 and 0.05 kWh/m^3 in CCD of the Mediterranean (2.78%) and ocean (3.87%) water sources, respectively.

Keywords: Seawater desalination; Ocean water desalination; Desalination energy; RO energy; Energy recovery; RO energy saving; Closed circuit desalination

1. Introduction

Increased reliance on potable water supplies for domestic applications and agricultural irrigation needs by reverse osmotic processes is bound to intensify in the future, due to already extensive consumption and rapid depletion of quality surface and ground water sources worldwide, combined with increasing needs due to population growth, rising standards of living, climate changes inflicted the global green-house effect, and other factors. Most of the worldwide population (>60%) already concentrates along seawater (SW) shores or within short distance; and therefore, most future needs for potable water supplies will most probably rely on SW desalination by reverse osmosis (RO) [1], which is already practiced on large scale worldwide as well as on some newly emerging techniques such as forward osmosis (FO) [1]. Seawater RO desalination (SWRO) is an energy intensive process (3–5 kWh/m^3) with ~75% of the total required as RO energy and the rest for pre- and post-treatment operations. Some 35–55% of total permeate production costs by SWRO manifest power expenses, therefore, low energy consumption is the single most important feature of any advanced SWRO desalination technology.

First reported by Loeb and Sourirajan [2] in the late fifties of the last century, conventional SWRO plug flew desalination (PFD) takes place inside a pressure vessel with 6–8 membrane elements connected in line and proceeds by the split of pressurized feed flow (Q_f) at inlet into two steams, one of none pressurized permeate (Q_p) and the other of pressurized brine (Q_b) with flow balance expressed by $Q_f = Q_p + Q_b$. The PFD process is based on hydrodynamic principles and the continuous flow of its three components (feed, brine, and permeate) simultaneously is an essential requirement in order to avoid adverse concentration polarization effects. A recent review article entitled. *The future of seawater desalination: energy, technology, and the environment* by Elimelech and Phillip [1] provides a state of the art account and future prospects of this rapidly growing important area. In contrast with conventional hydrodynamic PFD techniques, a newly conceived [3–5] approach to RO on the basis of hydrostatic principles is the so-called "closed circuit desalination" (CCD) technology which applies to SW [6–8] and brackish water [9–12], alike. The newly reported CCD technology is conceptually a batch desalination process ($Q_f = Q_p$) with internal concentrate recycling (Q_{cp}) made continuous with respect to permeate production by means of consecutive sequential techniques. The CCD approach to RO reveals exceptional performance benefits such as low energy consumption without need for energy recovery (ER), high recovery irrespective number of elements per pressure vessel, flexible control of membrane performance in compliance with manufacturers' specifications, a wide range of operational flux, and low scaling and fouling (including bio-fouling) characteristics unmatched by conventional techniques.

In light of the importance of RO energy consumption in SWRO desalination processes, the present article provides an extensive analysis of the energy saving prospects by SWRO-CCD compared with conventional SWRO-PFD techniques.

2. SWRO model of 2×ME4-CCD and 1×ME8-PFD units

The theoretical study considered hereinafter centers on a comparative model of two different eight elements units; one of a conventional ME8-PFD design (Fig. 1) and the other of an advanced 2×ME4-CCD design (Fig. 2) and performance of said units under identical flux conditions and temperature analyzed and compared with regards to energy consumption and permeates quality.

The conventional unit displayed in Fig. 1 comprises a single module (pressure vessel) with eight membrane elements for SWRO desalination, a single feed supply pump (FSP), a single high pressure pump (HP), and an ER device (e.g. PX or DWEER) which

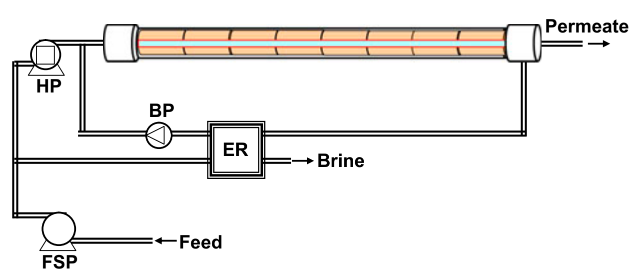

Fig. 1. A conventional single module eight-element SWRO-PFD design with ER means.

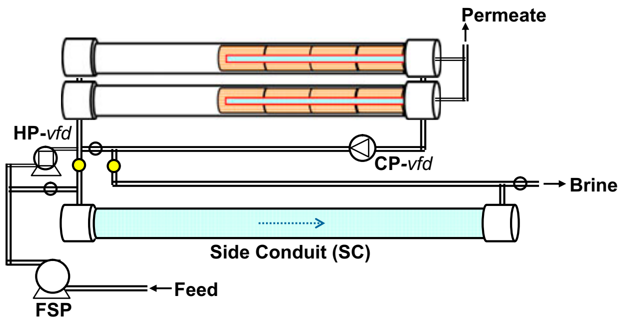

Fig. 2. Advanced SWRO-CCD unit design with two modules, each of four elements, with a side conduit and valve means (small circles) for occasional brine replacement by fresh feed inside the closed circuit without loss of brine energy.

also supplies part of the pressurized feed needs through a pressure booster pump (BP) in order to compensate for the pressure loss along the module.

The new CCD technology unit design displayed in Fig. 2 comprises two modules, each of four membrane elements for SWRO desalination, a FSP, a HP equipped with a variable frequency drive (*vfd*), a single circulation pump (CP) equipped with a *vfd*, and a side-conduit (SC) system 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 a SC for brine replacement by fresh feed at a desired system recovery (SR) level with negligible loss of energy. The configuration displayed in Fig. 2 describes a disengaged SC undergoing replacement of brine by fresh feed at near atmospheric pressure, while desalination is continued nonstop; thereafter, the SC is sealed, compressed, and left on stand-by for the next engagement. The CCD unit under review in Fig. 2 operates with fixed feed/permeate flow ($Q_f = Q_p$) under variable pressure conditions with flow rate controlled by flow-meter means through the *vfd* device of the HP pump. The operation of the unit (Fig. 2) is conditioned by concentrate recycling with CP in order to avoid adverse concentration polarization effects and allow for the dilution of the recycled concentrate with fresh feed at inlets to modules.

In contrast with the fixed flow-pressure operational modes of conventional SWRO techniques, CCD proceeds by a consecutive sequential process with each sequence comprising of cycles and the number of cycles determined by the selected module recovery (MR) and the desired SR. MR manifests the flow ratio of permeate ($Q_p = Q_f$) to module inlet flow and is expressed by $Q_p/(Q_p + Q_{cp})$ or by $Q_f/(Q_f + Q_{cp})$, and therefore, MR is fully controlled by the selection of Q_f or Q_p and Q_{cp}. SR stands for the recovery attained during a complete sequence and depends on the maximum allowed sequential pressure selection with a higher maximum sequential pressure selection concomitant with higher SR and vice versa.

Despite the inherent differences between PFD and the CCD methods, both units (Figs. 1 and 2) obey the same basic RO equations with regards to flow, pressure, and salt rejection. Accordingly, permeation flow (Q_p) and flux (F) are defined by the respective expressions (1) and (2) in terms of the net driving pressure (NDP) as defined by (3) with applied feed pressure in terms of flux defined by (4); wherein, Q_p stands for permeate flow, F for flux, A for permeability coefficient, p_{app} for applied feed pressure, Δp_c for concentrate-side pressure drop along the module, p_p for pressure of produced permeate, $\Delta\pi_{\text{av}}$ for average concentrate-side osmotic pressure (OP) difference, and π_p for the average permeate OP. Likewise, the average permeate concentration according to the basic RO theory is expressed by (5); wherein, C_p stands for the average permeate concentration, B for the salt diffusion coefficient, C_{fc} for the average concentrate-side concentration, pf_{av} for the average concentration polarization factor, and TCF for the temperature correction factor. The term pf_{av} is defined by (6); wherein, Y_{av} stands for the average element recovery defined by (7); wherein, Y stands for MR and n for the number of elements per module. Concentrate-side pressure drop (Δp_c) along a pressure vessel of n elements inside is expressed (psi) by (8); wherein, q stands for the arithmetic average concentrate-side flow (gpm) expressed by (9).

$$Q_p = A^* S^* (\text{NDP})^* (\text{TCF}) \tag{1}$$

$$F = Q_p/S = A^* (\text{NDP}) \tag{2}$$

$$\text{NDP} = p_{\text{app}} - \Delta p_c/2 - p_p - \Delta\pi_{\text{ay}} + \pi_p \tag{3}$$

$$p_{\text{app}} = F/A + \Delta p_c/2 + p_p + \Delta\pi_{\text{ay}} - \pi_p \tag{4}$$

$$C_p = B^* C^*_{\text{fc}} pf^*_{\text{av}} (\text{TCF})/F \tag{5}$$

$$pf_{\text{av}} = \text{EXP}[0.7^* Y_{\text{av}}] \tag{6}$$

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

$$\Delta p(\text{psi}) = 0.01^* n^* q^{1.7} \tag{8}$$

$$q(\text{gpm}) = (1/2)^* (\text{feed flow} + \text{concentrate flow}) \tag{9}$$

3. SWRO model analysis of 2×ME4-CCD and 1×ME8-PFD units

The conventional (Fig. 1) and CCD (Fig. 2) model units discussed hereinabove comprise the same number of elements and operate on the basis of the same RO Eqs. (1–9) and therefore, if contain the same type elements, supply with the same feed source, and operate at the same temperature under identical flux conditions should provide an ideal model system for comparison of energy consumption and permeate quality between the PFD and CCD SWRO techniques, a subject matter to be considered next. The results of a comparative analysis on the basis of the model designs in Fig. 1 (hereinafter "conventional technique") and Fig. 2 (hereinafter "CCD") are furnished in Table 1 for same type membrane elements (SWC6) and ocean water feed of 3.5% (ppm composition: Ca, 350; Mg, 1,272; Na, 10,700; K, 380; Ba, 0.05; Sr, 1.3; HCO_3, 107; SO_4, 3,200; Cl, 18,950; F, 1.4; B, 4.6; and SiO_2, 4.6) under identical flux conditions of 13 LMH at 25˚C assuming CCD MR of 25% and an absolute energy conversion (AEC) efficiency of 85% for the convention technique. A different terminology for AEC is *net energy transfer efficiency* or *wire to water energy efficiency*.

The comparative model system under review is based on a consecutive sequential CCD process performed with MR = 25% at fixed flux (13 LMH) under variable pressure conditions with each sequence of five discrete cycles (A1-Table 1) proceeding with a steady increase of module inlet concentrations (A2-Table 1) attained by the mixing of module outlet concentrates (A3-Table 1) with fresh pressurized feed and with a cumulative SR per cycle (A4-Table 1) manifesting the module outlet concentrations at each cycle. The applied pressures (p_{app}) for the sequential cycles (A5-Table 1) are derived from the theoretical expression (4) and calculated by means of an IMS-Design program with MR = 25%, on the basis of the respective module inlet concentrations (A2-Table 1) and the cumulative average applied pressure av-p_{app} (A6-Table 1) is the average pressure which takes account of the preceding cycles. The data for the module pressure difference Δp (A7-Table 1) was retrieved from the IMS-Design program and represents the compensation pressure requirements of the CP. The mean specific energy term of HP (A8-Table 1) is expressed by $(1/36)^*(\text{av-}p_{app})^*(1/f_{HP})$ and that of CP (A9-Table 1) by $(1/36)^*(1/Q_p)^*Q_{cp}{}^*\Delta p^*(1/f_{CP})$; wherein f_{HP} and f_{CP} stand for the efficiency ratio of the respective pumps. Noteworthy that the flow rates (Q_p and Q_{cp}) in the aforementioned power expressions are fixed terms. The combined RO specific energy of the entire CCD model system is expressed by HP + CP (A10-Table 1).

The conventional 1×ME8 SWRO-PFD design (Fig. 1) in the model analysis is presumed to operate with identical permeate flow (3.87 m^3/h), flux (13 LMH), ocean water feed (3.5%), and cumulative system recovery per stage (25, 40.0, 50.0, 57.1, and 62.5%) displayed for the CCD design (Fig. 2) process. The columns B1, B2, and B3 in Table 1 express the flow rates of feed, permeate (fixed flow: 3.87 m^3/h), and brine in the conventional (Fig. 1) unit of the model system and the pressure columns B4 expresses the IMS Design pressure requirements to reach the indicated (A4) system recovery starting with the fresh feed (3.5%) flow indicated in B1. The specific energy terms of the conventional (Fig. 1) unit in the model system are expressed in terms of feed (B5), brine (B6), and permeate (B7). The specific energy with respect to pressurized feed associated with HP is expressed by $SE_f = Q_f{}^*p_{IMS}{}^*(1/36)^*(1/Q_p)^*(1/f_{HP})$; the specific energy retrieved from brine expressed by $SE_b = SE_f{}^*(Q_b/Q_f)^*(AEC)$; wherein, AEC stands for AEC efficiency; and the net absorbed specific energy for permeate production is expressed by $SE_p = SE_f – SE_b$. This approach takes into account the AEC efficiency from start to end with increased AEC manifesting lower specific energy of permeates and vice versa. It should be noted that AEC is a factor derived [8] from the actual operation data of SWRO plants (e.g. flux, pressure, recovery, RO energy consumption, HP pump efficiency, temperature, etc.) irrespective of the ER type installed device and therefore, AEC is a none bias measure of energy utility effectiveness. A recent study [8], which takes account of reported performance experienced in some modern large SWRO desalination plants worldwide revealed an AEC efficiency range of 70–80%, irrespective of efficiency claims made for the ER devices.

The comparative performance data in Table 1 assumes an AEC efficiency factor of 0.85 which has not yet been realized by any of the modern large SWRO plants installed worldwide. The energy saved by CCD compared with conventional technique (C1-Table 1) is derived by the expression $100^*(1\text{-}SE_{CCD}/SE_{PFD})$; wherein, SE_{CCD} is the data in column A10 and SE_{PFD} is the respective data in column B7 of Table 1.

4. SWRO 2×ME4-CCD and 1×ME8-PFD model analysis results

While the performance of the conventional SWRO-PFD unit (Fig. 1), in the comparative model system specified in Table 1, does not require further explanations, this may not be the case with regard to the new

Table 1
Comparison between IMS Design data of the 1×ME8(E = SWC6) SWRO-PFD and the 2×ME4 (E = SWC6) SWRO-CCD units with ocean water (3.5%) feed under flux of 13 LMH at 25°C assuming CCD MR = 25% and AEC efficiency of 85%

2xME4 CCD-SWRO (25°C)

3.5	% Sea Water
2	No of Modules
4	No of Elements per Module
13.0	lmh Flux
37.2	m2 per Element
3.87	m3/h Peremate (Q_p=Q_f)
25	% Module Recovery (MR)
11.61	m3/h Q_{cp}

1xME8 PFD-SWRO (25°C)

3.5	% Sea Water
8	No of Elements per Module
1	No of Modules
13.00	lmh average
37.2	m2 per Element
3.87	m3/h permeate

ME4 Module Performance — Pump Efficiency: HP 0.85, CP 0.60

ME8 Module Performance — HP 0.85, AEC 0.85

ME4 CCD Cycles	Module Inlet ppm	Module Outlet ppm	System Recovery %	IMS-Design Data p_{app} bar	IMS-Design Data av-p_{app} bar	IMS-Design Data Δp bar	CCD Specific RO Energy HP kWh/m3	CCD Specific RO Energy CP kWh/m3	CCD Specific RO Energy HP+CP kWh/m3	Conventional RO flow Feed m3/h	Conventional RO flow PERM m3/h	Conventional RO flow Brine m3/h	IMS Design bar	CCD Specific RO Energy Feed kWh/m3	CCD Specific RO Energy Brine kWh/m3	CCD Specific RO Energy PERM kWh/m3	CCD Saved Energy %
0	3.50	3.50	0.00														
1	3.50	4.67	25.00	38.2	38.2	0.60	1.248	0.083	1.332	15.48	3.87	11.61	40.3	5.268	3.358	1.910	30.3
2	4.38	5.83	40.00	47.2	42.7	0.70	1.395	0.097	1.493	9.67	3.87	5.80	45.3	3.701	1.888	1.813	17.7
3	5.25	7.00	50.00	56.1	47.17	0.60	1.541	0.083	1.625	7.74	3.87	3.87	52.2	3.412	1.450	1.962	17.2
4	6.13	8.17	57.14	65.5	51.75	0.70	1.691	0.097	1.788	6.77	3.87	2.90	59.8	3.420	1.246	2.174	17.7
5	7.00	9.33	62.50	75.3	56.46	0.60	1.845	0.083	1.928	6.19	3.87	2.32	67.8	3.545	1.13	2.415	20.2
A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	A 10	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1

SWRO-CCD technology unit (Fig. 2), which operates on the basis of different principles of the following performance characteristics. The CCD unit under review is a continuously staged and continuously pressure-boosted system of number of stages defined by the number of sequential cycles determined by operational flux, MR, and applied pressure of maximum SR. The relationship between the number of cycles per sequence and SR under the conditions specified in Table 1 with flux of 13 LMH and MR = 25% are illustrated in Fig. 3 with inlet and outlet module concentration per cycle (Fig. 4) showing a strong dilution effect by the mixing of recycled concentrate with fresh pressurized feed at inlet to modules which increases with SR. The continuously sequential pressure boosting in the CCD process under review is illustrated in Fig. 5 together with the cumulative average pressure per cycle, which dictates the average energy consumption during the process.

The pressure requirements of the conventional unit (Fig. 1) as compared with the average pressure per cycle, or per stage, of the CCD unit (Fig. 2) in the model system under review according to the data furnished in Table 1 are illustrated in Fig. 6 as function of SR and the resulting RO specific energies are reveled in Fig. 7 with percent energy saving by CCD under comparable conditions with AEC = 0.85 illustrated in Fig. 8. The noteworthy RO energy saving by CCD as function of SR displayed in Fig. 8 represents AEC = 85%, a value not yet attained in any of the large modern conventional SWRO plants worldwide which normally operate in the AEC range of 70–80%, and sometime even below. Accordingly, the actual RO energy saving by CCD compared with the conventional technique exceeds the values indicated in Fig. 8, which is an issue to be considered next.

The model simulations in Table 1 were extended to include the AEC ratio range 1.00–0.70 (1.00, 0.95, 0.90, 0.85. 0.80, 0.75, and 0.70) in order to ascertain the broad aspects of RO energy saving by the continuously staged and pressure-boosted CCD process relative to conventional techniques under the same flux and SR conditions, and the results of this analysis are displayed in Fig. 9. Although reported information on AEC efficiencies of large conventional SWRO desalination plants is rather scarce, such information can be made available from reported performance data of specific RO energy, recovery, applied pressure, temperature, and efficiency of

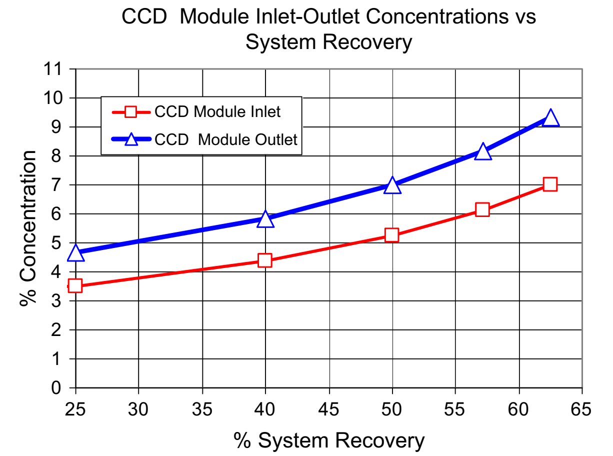

Fig. 4. Illustration of the dilution effect at inlet to CCD modules vs. SR during the continuously staged process according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25%.

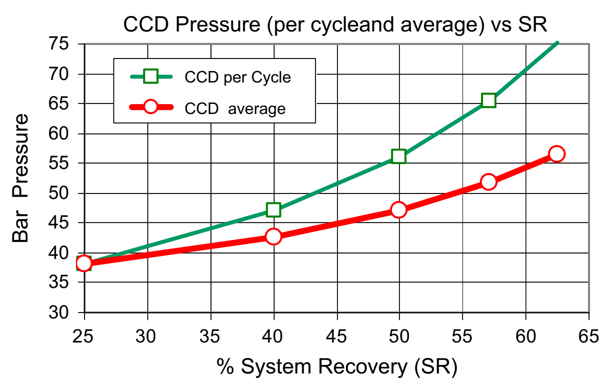

Fig. 5. Illustration of the actual and average CCD sequential pressures vs. SR during the continuously staged and pressure-boosted process according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25%.

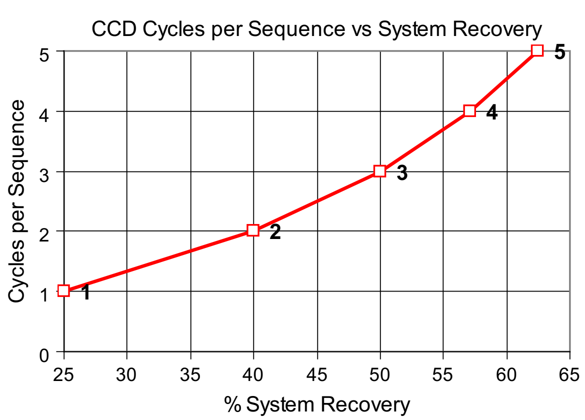

Fig. 3. Illustration of the continuously staged CCD process vs. SR according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25%.

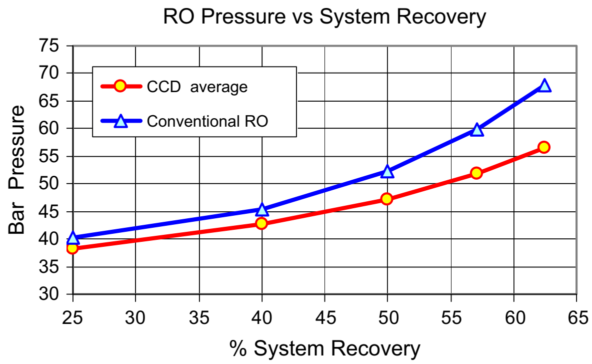

Fig. 6. Illustration of the actual pressure requirements of a conventional unit compared with the average sequential pressures requirements of a CCD unit at the same SR according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25%.

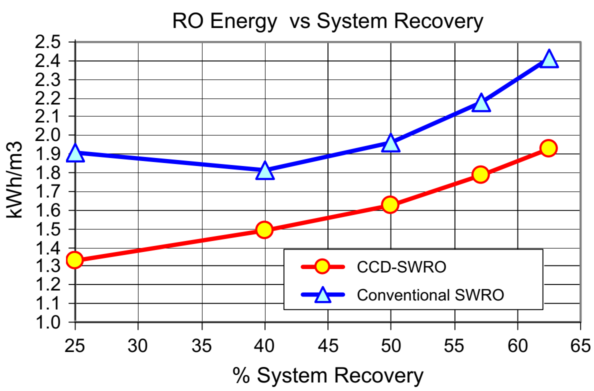

Fig. 7. Illustration of conventional RO energy assuming AEC = 85% compared with CCD energy at the same SR according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25%.

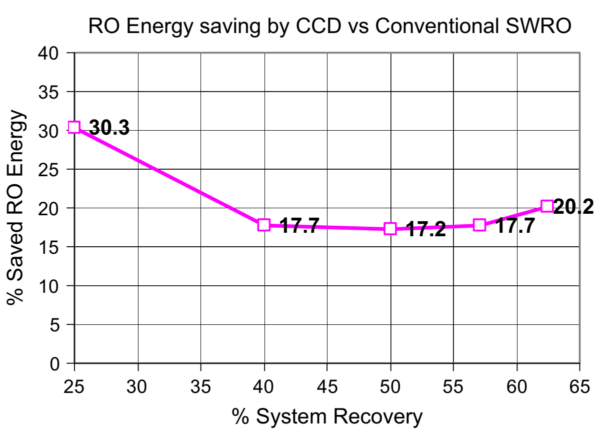

Fig. 8. Illustration of the RO energy-saved by the CCD unit compared with a conventional unit at the same SR according to the data in Table 1 for ocean water (3.5%) at 13 LMH and 25˚C with MR = 25% and AEC = 85%.

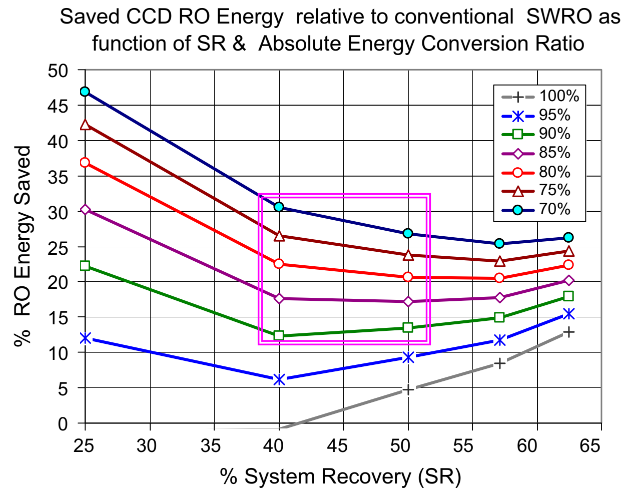

Fig. 9. Illustration of the percent saved RO energy by CCD compared with the conventional techniques at the same SR according to the procedure in Table 1 in the context of ocean water (3.5%) at 13 LMH and 25˚C with MR = 25% and AEC of 70–100%.

pumps by a procedure already reported elsewhere [8]. Reasonable assessment of AEC is possible also from partial performance data of plants, since large conventional SWRO plants are known to operate in a confined recovery range (47 ± 3%) with high efficiency (84 ± 2%) pressurizing pumps under the recommended applied pressures derived from their membranes' design programs. Currently available performance data of large SWRO desalination plants is highly consistent with AEC of 70–80% and this implies that the actual RO energy saved by CCD is of the order of 17–31% depending on recovery (Fig. 9).

The model performance analysis of the conventional (Fig. 1) and CCD (Fig. 2) units with the same elements (SWC6) under the same flux, system recovery, and temperature conditions already considered above in the context of energy consumption, may also be extended to include the quality of produced permeate. The quality of RO permeates according to the basic RO expression in (5) implies about the same salt concentration (C_p) for units with identical B, C_{fc}, TCF, and F terms of somewhat different pf_{av} terms. The IMS Design program for the SWC6 membrane elements which has been used to obtain the applied pressure data (p_{app}) in Table 1 also provided the beta (pf_{av}) values range 1.01–1.02 for both model units under the specified operational conditions. Accordingly, permeate quality produced by CCD and conventional techniques under the same flux conditions is essentially identical and this despite the major RO energy savings encountered with the former method.

The theoretical comparative model of CCD and PFD considered hereinabove is based on the same principle RO equations and the relativity of the predicted results of energy consumption and salts rejection by this theoretical model under identical conditions shall remain unchanged irrespective of type of membrane elements. In simple terms, the percent saved energy by CCD is independent of the selected type of membrane element in the model analysis and both CCD and PFD shall yield the same quality permeates at the same recovery level. In contrast with CCD, PFD is not an absolute ER technique and the efficiency of ER from the disposed pressurized brine flow at the entire system level is an important parameter in the theoretical model. The AEC efficiency of conventional SWRO plants can only be assessed from their actual operational data and this experimental parameter is found to be substantially lower than claimed efficiency of installed ER devices.

5. Pressure, flow, and energy simulations for CCD ME4

CCD is a consecutive sequential batch process of enormous flexibility performed under fixed flow and variable pressure conditions with each sequence comprises fixed duration cycles and time period (T_s) required to reach a desired SR expressed by (10); wherein, V stands for the fixed intrinsic free volume of the batch reactor, Q_f for the fixed pressurized feed flow supplied by HP for the fixed permeate production flow ($Q_p = Q_f$), and SR for sequence recovery. MR per cycle in this process is defined by (11); wherein, Q_{cp} stands for the fixed internal concentrate recycling cross flow without which desalination is impossible due to immediate rise of concentration polarization. MR in CCD is dictated by the selection of Q_p and Q_{cp}. The mixing of pressurized feed and recycled concentrate at inlet to modules during the CCD cycles of the consecutive sequential process create a dilution effect with module inlet concentration expressed by (12); wherein, C_{mi} stands for module inlet concentration, Q_f for fixed feed flow, C_f for feed concentration, C_{mo} for module outlet concentration, and Q_{cp} for the fixed recycled concentrate cross flow. The applied pressure (p_{app}) to RO Eq. (4) relates to OPs instead of concentrations, and the knowledge of feed concentration (C_f) and its OP (π_f) enables to establish the π_f/C_f ratio (e.g. bar/% ratio) per said defined feed source and this ratio may apply for the conversion of modules' inlet (C_{mi}) and outlet (C_{mo}) concentrations to their respective OP terms π_{mi} and π_{mo}. The knowledge of flow rates and pressures provide the computation means of energies.

$$T_s = \mathrm{SR}^* V/[Q_f^*(100 - \mathrm{SR})] = \mathrm{SR}^* \mathrm{V}/[Q_p^*(100 - \mathrm{SR})] \quad (10)$$

$$\mathrm{MR}(\%) = Q_f^* 100/(Q_f + Q_{cp}) = Q_p^* 100/(Q_p + Q_{cp}) \quad (11)$$

$$C_{mi} = \left[Q_f^* C_f + Q_{cp}^* C_{mo})\right]/(Q_f + Q_{cp}) \quad (12)$$

Performance simulation of the CCD ME4 module also requires paying attention to the intrinsic volume of the closed circuit (V), which dictates the CCD cycle period and sequence duration to reach a predefined system recovery level. The CCD cycle period is the time required to achieve a complete recycle of V through the closed circuit and therefore, defined as $60 * V/Q_{cp}$ in minute per CCD-cycle; when, volume is expressed by m^3 and flow by m^3/h. Constant Q_{cp} implies a fixed cycle period during the consecutive sequential process with sequence duration expressing the cumulative cycles' periods required to reach the predefined system recovery.

Simulated sequential pressures, flow rates, and energies for ME4 in SWRO-CCD of ocean water (3.5%) according to the aforementioned principles are illustrated in Fig. 10 on the recovery scale and in Fig. 11 on the time scale. The sequential CCD operation under fixed flow and variable pressure conditions dictates the energy demand of this batch process which is made continuous with respect to permeate production by means of a consecutive sequential process. The data furnished in Fig. 10 with respect to pressures (A), flow rates (B), and energies (C) reveals the attainment of 50% recovery by a sequence of three complete cycles with an average energy of 1.61 kWh/m^3 as compared with 1.62 kWh/m^3 by the model analysis in Table 1. Recycling flow rate by CP of 5.8 m^3/h in a closed circuit of 178 liter implies a cyc1e duration of 1.83 min (60*0.178/5.8) and the simulated pressures (A), flow rates (B), and energies (C) on the sequential time scale revealed in Fig. 11. Attainment of 50% recovery by three complete cycles, each of 1.84 min, implies total sequence duration of 5.52 min with average energy consumption of 1.61 kWh/m^3. The time scale simulation also implies a sequential engagement period of 1.84 min between the closed circuit and side conduit for brine replacement by fresh feed and a 3.68 (2*1.84) min sequential period duration of disengaged configuration during which period the side conduit is decompressed/recharged/

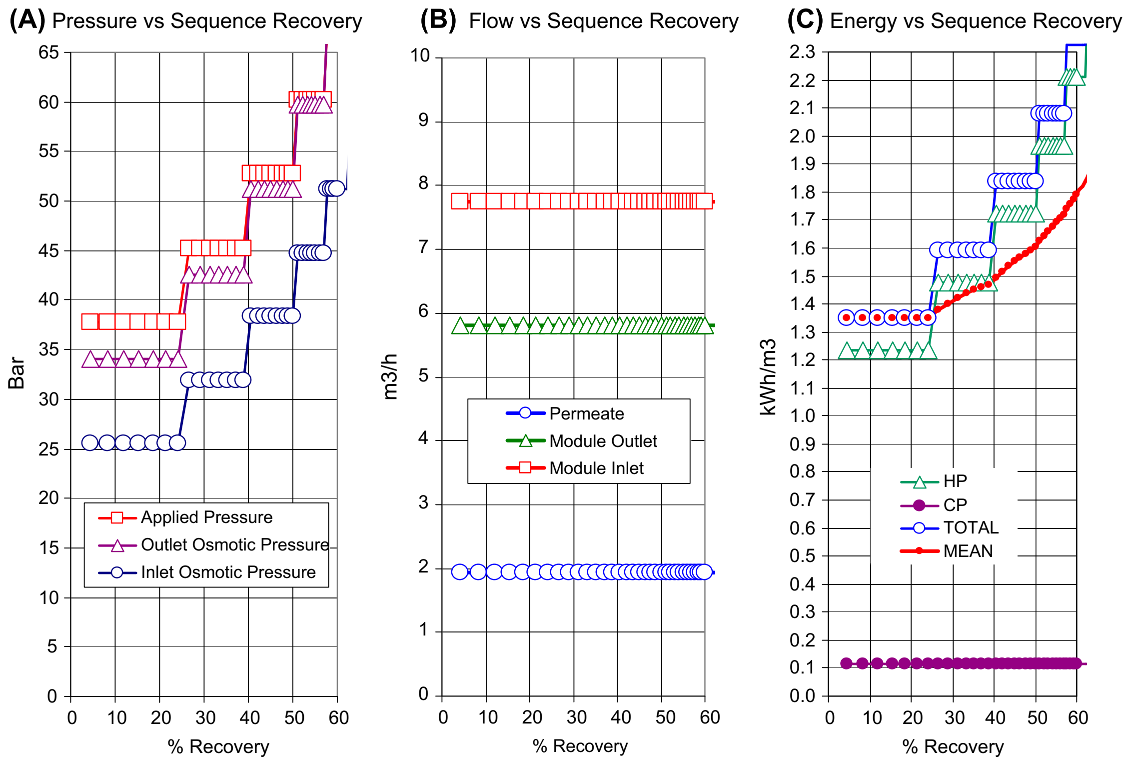

Fig. 10. Single module, single sequence ME4 (E = SWC6) SWRO CCD simulations of pressures (A), flow rates (B), and energies (C) on the recovery scale of ocean water (3.5%) under the conditions specified in Table 1 of 1.93 m^3/h HP (85% *eff.*); 5.80 m^3/h CP (60% *eff.*); flux = 13 LMH; MR = 25%; Δp = 0.60 bar; π_f/C_f = 7.30 bar/%; temperature = 25˚C; and V = 178 l closed circuit intrinsic volume.

compressed and left on stand-by for the next engagement.

The CCD simulations in Figs. 10 and 11 illustrate the principle features of the CCD technology with regard to low energy consumption along the diagonal curve as a function of system recovery without the need for ER and the high recovery achieved by concentrate recycling as function of the sequential period instead of the number of lined elements in conventional modules.

6. Pressure-volume work model for theoretical assessment of CCD energy

Most (>90%) of the energy requirements of SWRO–CCD processes originate from the HP with an additional small amount (<10%) associated with the concentrate recycling pump (CP). Since CCD is performed with fixed pressurized feed flow identical to that of permeate ($Q_f = Q_p$) along the variable applied pressure (p_{app}) diagonal curve, the specific energy related to HP is a function of the average pressure along the pressure diagonal and expressed in kWh/m^3 by $(p_i + p_f)/2/36/eff.$; wherein p_i and p_f stand for the respective initial and final sequential pressures, and *eff.* for the efficiency factor of the pump. For instance, assuming π_f/C_f ratio of 7.30 for feed and concentrate salinity variations as function of recovery during CCD sequences for ocean (3.5%), Mediterranean (4.0%), and gulf (4.5%) sources enables to generate the OP curves in Fig. 12 for the theoretical minimum energy requirements ($p_{app} \approx \pi_c$) associated with HP. Such theoretical minimum CCD energy requirements of HP are displayed in Fig. 13(A) for HP efficiency of 100% and in Fig. 13(B) for HP efficiency of 85% on the basis of the integrated hydraulic volume–pressure work expression $V_p{}^*dp_{app}$; wherein, p_{app} stands for applied pressures along the system recovery curve and V_p for a fixed permeation volume unity ($V_p = 1.0\,m^3$). The theoretical minimum CCD HP energy requirements are said for $p_{app} \approx \pi_c$ and imply an infinitesimally small flux, or NDP. The theoretical CCD HP energy requirements under real flux conditions (e.g. ~13 LMH) can be derived from the aforementioned hydraulic volume–pressure work model expression $V_p{}^*dp_{app}$ by applying $p_{app} = \pi_c +$ NDP and the results of such an approach using NDP = 8.7 bar are displayed in Fig. 14 for various SW

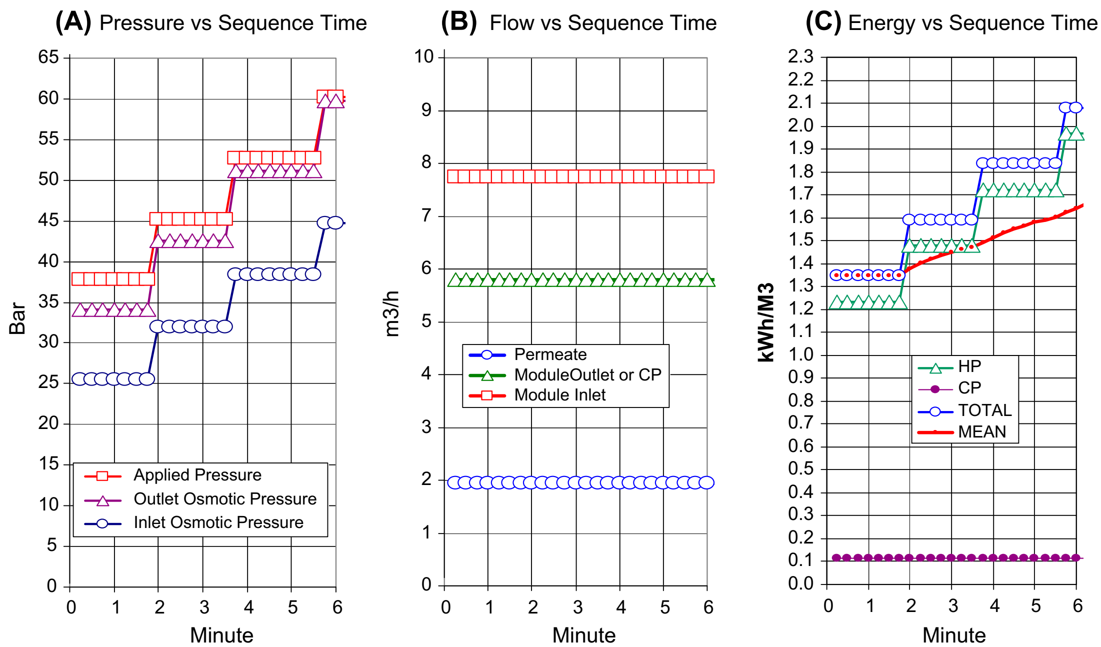

Fig. 11. Single module, single sequence ME4 (E = SWC6) SWRO CCD simulations of pressures (A), flow rates (B), and energies (C) on the time scale of ocean water (3.5%) under the conditions specified in Table 1 of 1.93 m^3/h HP (85% *eff.*); 5.80 m^3/h CP (60% *eff.*); flux = 13 LMH; MR = 25%; $\Delta p = 0.60$ bar; $\pi_f/C_f = 7.30$ bar/%; temperature = 25°C; and $V = 178$ l closed circuit intrinsic volume.

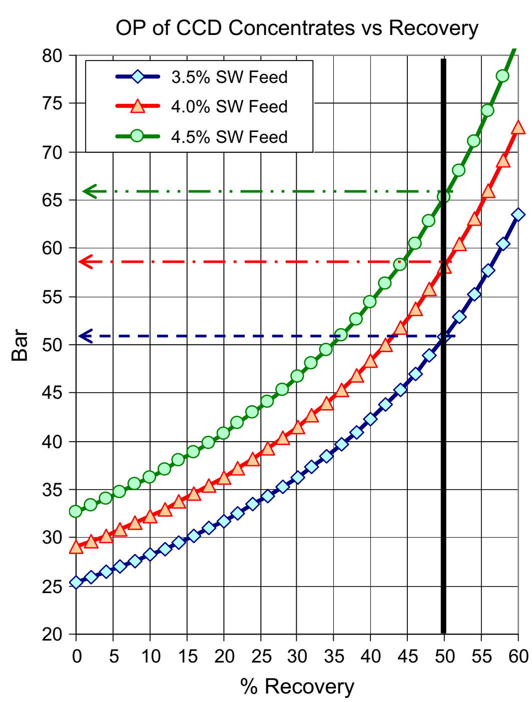

Fig. 12. OP of feed and concentrates as a function of CCD recovery up to 60% for three different SW sources with emphasis on OP at start and at 50% SR.

sources. The selected NDP in Fig. 14 is that of the ME4 (E = SWC6) module which operates at 13 LMH under the specified conditions in Table 1.

Theoretical minimum HP energy required to initiate CCD of ocean water (3.5%) is 1.05 kWh/m^3 with the pump's efficiency of 100% according to Fig. 13(A) and 1.24 kWh/m^3 with pump's efficiency of 85% according to Fig. 13(B), and with negligible flux in the absence of concentration polarization effects these minimum values are attained essentially under hydrostatic conditions. The projected theoretical CCD energies for 50% recovery at 13 LMH of ocean water (3.5%) with ME4 modules are 1.62 kWh/m^3 according to the IMS design model analysis in Table 1 and 1.61 kWh/m^3 according to the simulations in Figs. 10(C) and 11(C) and these essentially identical results agree with the sum (1.62 kWh/m^3) of 1.54 kWh/m^3 for HP in Fig. 14 and 0.083 kWh/m^3 for CP from the data in Table 1.

7. Actual SWRO energies of CCD and conventional plants

Reported data of SWRO energy consumption for large and modern Mediterranean desalination plants include 2.73 kWh/m^3 for the SWRO-PX plant in Hadera, Israel [13]; 2.98 kWh/m^3 for the SWRO-DWEER plant in Ashkelon, Israel [14]; 2.95 kWh/m^3

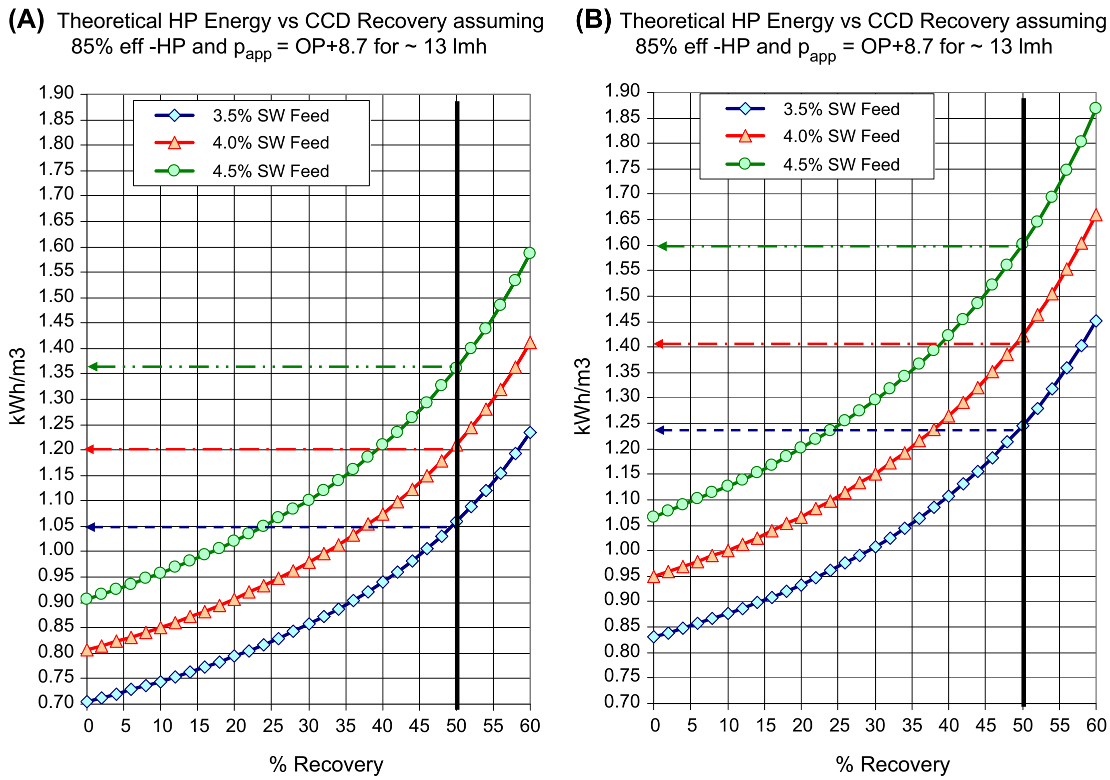

Fig. 13. Theoretical minimum HP energy requirements as function of CCD recovery for three different SW sources with HP efficiency of 100% (A) and 85% (B), and emphasis on start and 50% recovery.

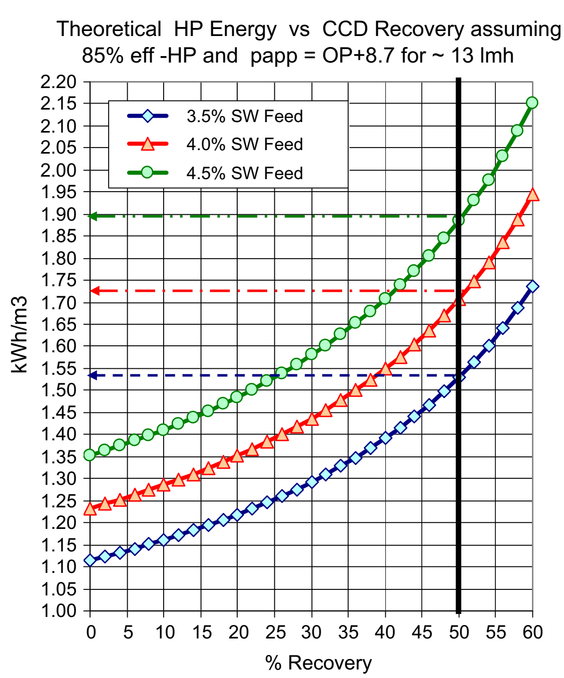

Fig. 14. Theoretical HP energy requirements to initiate CCD and proceed to 60% recovery assuming applied pressure is greater by 8.7 bar than OPs for a 13 LMH process with 85% efficiency of HP.

for the SWRO-Pelton unit or 2.70 kWh/m^3 for the Pelton-PX Hybrid unit in Palmachim, Israel [15]; and the projected 2.65 kWh/m^3 value for the SWRO-DWEER plant in Soreq, Israel [13], which is under construction. Likewise, reported RO energy of some large and modern ocean water desalination plants include 2.47 kWh/m^3 for the SWRO-PX plant in Perth, Australia (3.4%) [16] and 3.11 kWh/m^3 for the SWRO-DWEER plant in Tuas, Singapore (max. 3.5%) [13].

Compared with the aforementioned energy consumption of conventional plants with advanced ER means, Mediterranean water (4.1%) CCD of 47.0 ± 2.0% recovery by means of the 4xME4 (E = SWC6) unit revealed [6–7] the RO energy range 1.85–2.25 kWh/m^3 in the respective flux range 8–17 LMH, with HP pump efficiency of 82 ± 2% and CP pump efficiency of 25 ± 5% in the temperature range 21.5 ± 1.5°C. The normalized (25°C; 85% *eff.* of HP and 60% *eff.* of CP) experimental SWRO-CCD energy results for Mediterranean water at flux of ~13 LMH under said conditions was found to be ~1.80 kWh/m^3 with modeling projections [17] of ~1.65 kWh/m^3 for typical ocean water (3.5%).

The experimental CCD energy plot vs. flux for Mediterranean water (4.1%) in Fig. 15(A) and for ocean water (3.5%) in Fig. 15(B) show linear relationships

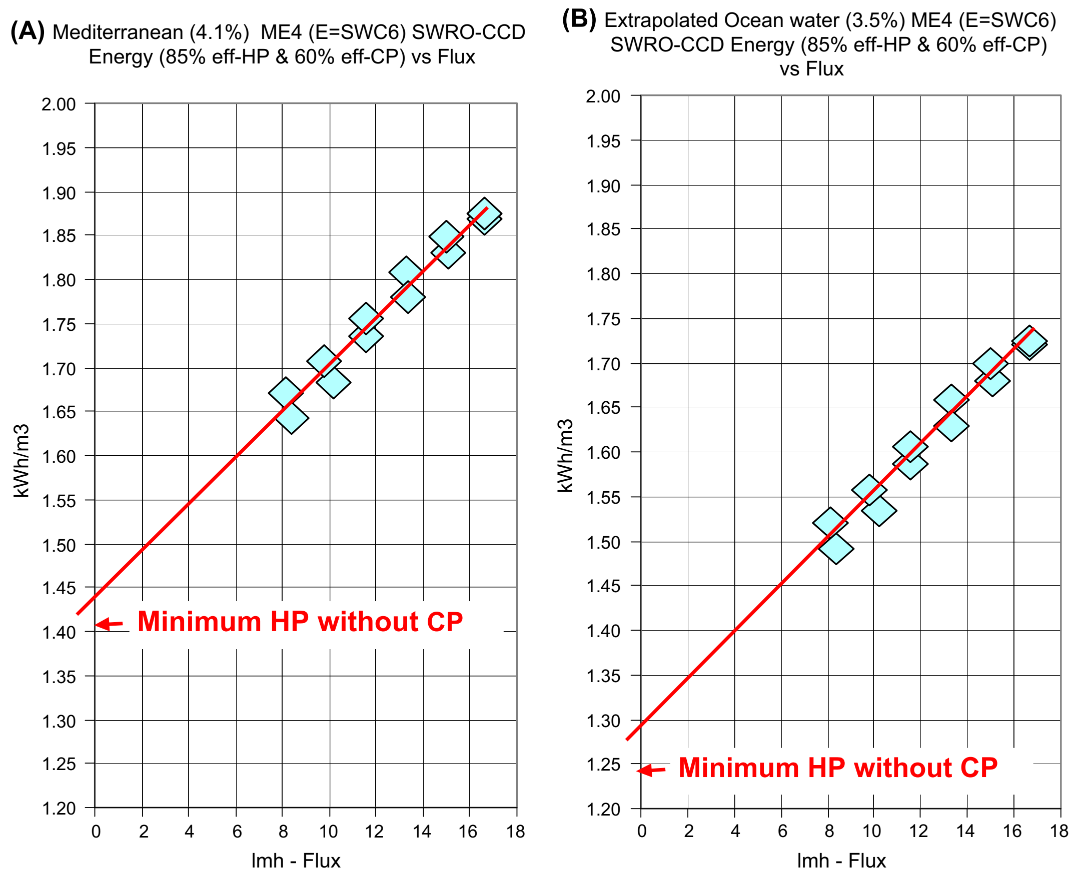

Fig. 15. Experimentally driven normalized (25˚C; 85% HP-*eff.*; 60% CP-*eff.*) SWRO energies of 4*ME4 (E = SWC6) CCD unit design vs. flux for Mediterranean water of 4.1% (A) and for ocean water of 3.5% (B) with extrapolated zero flux energies.

with zero flux intercept of minimum energy at 1.44 and 1.29 kWh/m^3, respectively. These experimentally extrapolated zero flux energies incorporate both HP and CP components and therefore, are expected to be somewhat higher compared with the theoretically derived minimum HP (85% *eff.*) in Fig. 13(B) on the basis of the pressure-volume work model for 50% recovery without any CP contribution. The Mediterranean water difference (0.04 kWh/m^3) between the CCD experimentally extrapolated minimum of 1.44 kWh/m^3 in Fig. 15(A) and the HP theoretical model minimum of 1.40 kWh/m^3 in Fig. 13(B) manifests the small energy contribution of CP energy in the former case under said negligible flux conditions and the respective difference (0.05 kWh/m^3) between ocean water of 1.29 kWh/m^3 in Fig. 15(B) and the HP theoretical model minimum of 1.24 kWh/m^3 in Fig. 13(B) manifests the same. The CP energy contributions under negligible flux conditions are expected to be rather small, since at this point the infinitesimally small permeation flux takes place essentially under hydrostatic pressure conditions with a negligible concentration polarization effect without need for its control by cross flow. The relationships between energy and flux on basis of theoretical models and experimental results discussed hereinabove are noteworthy for the classification of SWRO-CCD as a near AEC technology without need for ER. In simple terms, all the pressurized feed (Q_f) in CCD is converted to permeate (Q_p) with $Q_f = Q_p$ without any loss of brine energy and a small additional fraction of energy is required by CP to enable effective cross flow for concentration polarization control. The cross flow energy according to the model analysis in Table 1 requires 4.7–6.7% of the total energy in the respective recovery range 25–62.5%. The somewhat lower CCD CP energy requirements under 25% sequential recovery are manifested by 0.04 of 1.44 kWh/m^3 (2.78%) for Mediterranean water and 0.05 of 1.29 kWh/m^3 (3.87%) for ocean water already discussed in the context of Fig. 15A and B.

Part of the large energy consumption difference encountered between CCD and conventional desalination techniques for Mediterranean and oceans water sources may be due to the use of the low permeability coefficient (1.729 l/m^2/h/bar) membranes (SWC6) with CCD. Nevertheless, most of the difference in energy consumption between said techniques originates from their energy efficiencies and are manifested by their AEC efficiencies. AEC efficiency is an experimentally determined parameter also referred to as *net energy transfer efficiency* and *wire to water energy conversion efficiency,* which expresses the fraction of energy at inlet to RO unit which translates to permeate production and in conventional techniques, this parameter also takes into account the efficiency of ER from brine. In reference to AEC of conventional SWRO plants, noteworthy are the data reported [15] for the Palmachim plant in Israel wherein the energy consumption of 2.70 kWh/m^3 with the ERT-PX HYBRID ER device was claimed to proceed with *net energy transfer efficiency … just over 76% at the best efficiency point*, and most probably significantly less below this high efficiency point. Since the Palmachim plant in Israel is noted for its low energy consumption (2.70 kWh/m^3), the claimed 76% or less *net energy transfer efficiency* may suggest that most other conventional SWRO plants worldwide are operated with 70–80% AEC efficiency or less [8]. Reference made hereinabove to large and modern conventional SWRO plants is no coincidence, since such plants are normally well designed of high standards and carefully operated with high efficiency pressurizing pumps. Accordingly, the SWRO energy results obtained in such large commercial plants represents the state of the art level of the conventional desalination technology with limited prospects for further improvements.

8. Concluding remarks

Modern, large conventional SWRO desalination with advanced ER means normally perform at the state of the art level with very little room for further improvements of energy consumption. The various energy aspects of SWRO have received considerable attention over the past decade [1,18,19] and the interest this important subject matter as not declined as evident by the recent elegant study by Lie et al. [20], wherein an ideal RO process is defined in terms of energy efficiency by analyzing the contributions of the various system's components and in particular, the energy efficiency of the cross flow at various recover levels. The extensive practical and theoretical knowledge gained on SWRO processes makes it rather clear that future improvements in RO will require innovations which depart from the principles of the existing plug flow desalination techniques and this approach has led to the development of CCD.

The newly conceived CCD is a consecutive sequential batch process of a selected number of cycles per sequence performed under fixed flow and variable pressure conditions without need of ER from pressurized brine in a continuously staged and pressure-boosted system along the sequential cycles with pressurized feed at inlet to module mixed with recycled concentrate. In the CCD process under review, both flow rates of pressurized feed and permeate are the same and therefore, this process proceeds with near absolute RO energy conversion efficiency without need to recover energy from brine. The sequential pressure boosting nature of CCD implies an average absolute HP energy consumption as function of sequential recovery, or in simple terms, along the average absolute RO energy consumption diagonal curve during sequential cycles. The average diagonally raised absolute energy consumption of CCD as function of recovery is somewhat moderated by the dilution effect, due to the mixing of recycled concentrated with the pressurized feed at inlet to modules. The overall energy consumption of CCD also contains a small energy component due to CP which according to model analysis in Table 1 corresponds for 4.7–6.7% of the total energy in the respective recovery range 25–62.5%. The absolute CP energy contribution under 25% recovery from extrapolated experimental results and the pressure-volume work model data have been found to be 0.04 of 1.44 kWh/m^3 for Mediterranean water (4.1%) and of 0.05 of 1.29 kWh/m^3 for ocean water (3.5%), or 2.78 and 3.87% of the respective energy needs under negligible flux conditions.

These experimentally extrapolated CCD energy results of near AEC efficiency without the need of ER means are fully supported by model analyses and process simulation techniques which provide a comprehensive theoretical background for the understanding of this noteworthy unique approach to desalination.

CCD is currently the only continuously staged and pressure boosted available SWRO technology. A conventional SWRO-staged design was proposed [21] in the past, in order to reduce the RO energy requirements; however, such an expensive design approach with staged pressure vessels and BPs on top of the principle pressurizing and ER means will still be confined to applied pressures under 80 bar, recovery around 50% and energy efficiency determined by efficiency of pumps and the pressure-exchangers ER means. Counting the efficiencies of the aforementioned pressure-related components and taking into account the practiced AEC efficiency of existing modern SWRO plants may suggest the prospects of only limited improvement in energy consumption by such an approach.

Acknowledgments

Funds to Desalitech Ltd., by AQUAGRO FUND L. P. and by Liberation Capital LLC are gratefully acknowledged.

References

[1] M. Elimelech, W.P. Phillip, The future of seawater desalination: Energy, technology, and the environment, Science 333 (2011) 712–717.
[2] S. Loeb, S. Sourirajan, American chemical society advances in chemistry series, ACS 38 (1963) 117–132.
[3] A. Efraty, Variable Pressure Closed Circuit Desalination, PCT International Publication No WO O3/013704 A2 20.02.2003.
[4] A. Efraty, Apparatus for continuous closed circuit desalination under variable pressure with a single container, US Patent No 7,628,921.
[5] A. Efraty, Continuous closed-circuit desalination apparatus without containers, US Patent No 7,695,614.
[6] A. Efraty, N.R. Barak, Z. Gal, Closed circuit desalination—A new low energy high recovery technology without energy recovery, Desalin. Water Treat. 31 (2011) 95–101.
[7] A. Efraty, N.R. Barak, Z. Gal, Closed circuit desalination series no. 2: New affordable technology for sea water desalination of low energy and high flux using short modules without need of energy recovery, Desalin. Water Treat. 42 (2012) 189–196.
[8] A. Efraty, Closed circuit desalination series no. 6: Conventional RO compared with the conceptually different new closed circuit desalination technology, Desalin. Water Treat. 41 (2012) 279–295.
[9] A. Efraty, Closed circuit desalination series no. 3: High recovery low energy desalination of brackish water by a new two-mode consecutive sequential method, Desalin. Water Treat. 42 (2012) 256–261.
[10] A. Efraty, Closed circuit desalination series no. 4: High recovery low energy desalination of brackish water by a new single stage method without any loss of brine energy, Desalin. Water Treat. 42 (2012) 262–268.
[11] A. Efraty, Z. Gal, Closed circuit desalination series no 7: Retrofit design for improved performance of conventional BWRO systems, Desalin. Water Treat. 41 (2012) 301–307.
[12] A. Efraty, J. Septon, Closed circuit desalination series no. 5: High recovery, reduced fouling and low energy nitrate decontamination by a cost effective BWRO-CCD method, Desalin. Water Treat. 49 (2012) 384–389.
[13] N. Voutchkov, Membrane seawater desalination—Overview and recent trends, in: Proceedings of the IDA Conference, November 2–3, 2010, Riverside, CA, USA.
[14] B. Liberman, Present and future: Energy efficiency seawater desalination, in: Proceedings of the IDA Conference, November 2–3, 2010, Riverside, CA, USA.
[15] A. Hermoni, Actual energy consumption and water cost for the SWRO systems at Palmachim—Case history, in: Proceedings of the IDA Conference, November 2–3, 2010, Riverside, CA, USA.
[16] M.A. Sanz, R.L. Stover, Low energy consumption in the Perth seawater desalination plant, in: Proceedings of the IDA World Congress, Maspalomas, October 21–26, 2007 MP07.
[17] R.L. Stover, N. Efraty, Record low energy consumption with closed circuit desalination, in: Proceedings of the IDA World Congress, Perth, September 4–9, 2011, IDAWC/PER11-375.
[18] L. Song, J.Y. Hu, S.L. Ong, W.J. Ng, M. Elimelech, M. Wilf, Emergence of thermodynamic restriction and its implication for full-scale reverse osmosis processes, Desalination 155 (2003) 213–228.
[19] L. Song, J.Y. Hu, S.L. Ong, W.J. Ng, M. Elimelech, M. Wilf, Performance limitation of the full-scale reverse osmosis process, J. Membr. Sci. 214 (2003) 239–244.
[20] C. Liu, K. Rainwater, L. Song, Energy analysis and efficiency assessment of reverse osmosis desalination process, Desalination 276 (2011) 352–358.
[21] A.Z. Zhu, P.D. Christofides, Y. Cohen, Effect of thermodynamic restriction on energy cost optimization of RO membrane water desalination, Ind. Eng. Chem. Res. 48 (2009) 6010–6021.