Desalination and Water Treatment
www.deswater.com

41 (2012) 279–295
March

1944-3994/1944-3986 © 2012 Desalination Publications. All rights reserved
doi: 10.1080/19443994.2012.664741

Closed circuit desalination series no-6: conventional RO compared with the conceptually different new closed circuit desalination technology

Avi Efraty*

Desalitech Ltd., P.O. Box 132, Har Adar 90836, Israel
Tel. +972 52 4765 687; Fax: +972 2 5700262; email: avi@desalitech.com

Received 21 September 2011; Accepted 19 January 2012

ABSTRACT

Since first reported on October 2010 (EuroMed 2010, "Desalination for clean water and energy", 3–7 October, Tel Aviv, Israel), the large volume of diverse experimental results recently published on closed circuit desalination (CCD) technology reveal new state-of-the-art technology of high recovery; low reverse osmosis (RO) energy in the absence of energy recovery; reduced scaling and fouling with a wide range of operational flux without exceeding membranes' test condition specifications and flexible online control of all principle parameters in desalination processes independent of each other; of unmatched performance characteristics compared with the widely practised conventional plug flow desalination methods. In order to realize the scope and prospects of the new CCD technology on the basis of its performance characteristics which appears to presently meet most, if not all, long-term (20 years) targets of the growing worldwide desalination industry with high cost effectiveness, the present document provides an updated summary of all available results together with a critical evaluation in comparison with conventional Plug Flow technology. The results of this critical comparative study reported herein provide the desalination industry with a new technology ready for immediate application, which addresses essentially all beneficial aspects of RO.

Keywords: Closed circuit desalination; High recovery; High flux; Low energy; Reduced fouling; Seawater; Brackish water; Commercial unit performance

1. Introduction

A recent review article by Elimelech and Philip [1] entitled "The future of seawater desalination: energy, technology, and the environment" summarizes the state-of-the-art and future prospects of this rapidly growing area of significant global importance. This review article contains only brief comments on "cyclic desalination"—published information on closed circuit desalination (CCD) started to appear in press only very recently. The present work provides an insight into advanced CCD technology of exceptional performance characteristics, unmatched by any of the conventional plug flow desalination (PFD) technology, which stands an excellent chance of becoming the future technology of choice for membrane desalination. The newly emerging CCD technologies, first presented at the EuroMed 2010 conference in Tel Aviv, are state-of-the-art and versatile with respect to low energy consumption without the need for energy

---

*Corresponding author.

recovery (ER), high recovery, wide range operational flux, low scaling and fouling characteristics, flexible control of membrane performance in compliance with manufacturers' specifications and many other benefits and advantages as compared to conventional technology. This comparative study outlines the conceptual principles of the CCD technology as compared with conventional PFD technology and provides insight to the rapidly growing knowledge on CCD techniques and their commercial applications.

2. Conventional PFD technology

Conventional RO is a hydrodynamic PFD process which remained essentially unchanged since inception in the late 50s of the last century by Loeb and Sourirajan [2] except for major improvements in semi-permeable membranes and ER means. PFD proceeds by the splitting of pressurized feed flow (Q_f) at the inlet of pressure vessels, of *n* membrane elements per vessel arranged in line, into two streams one of un pressurized permeate (Q_p) and the other of pressurized brine (Q_b) with a flow balance expressed by $Q_f = Q_p + Q_b$. The process is based on hydrodynamic principles which require the continuous flow of all three components simultaneously.

Excess pressurized feed flow at the inlet to PFD vessels serves to control concentration polarization at the appropriate level to allow effective desalination. PFD is a *single-mode technology* with pressurized feed flow of defined composition at the inlet to head element, combined with defined number (*n*) of elements in line per each vessel, dictates the entire system's performance with respect to flow, pressure and salinity, recovery (*R*), power (*P*) demand and specific energy (SE) consumption. PFD is characterized by low energy efficiency, unless the energy stored in the pressurized brine flow is being saved by ER means.

The basic RO equations which apply to PFD are considered next assuming for simplicity new membranes (fouling factor [FF] = 1.0) at 25 °C (temperature correction factor [TCF] = 1.0). Permeate flow (Q_p) is expressed by (1); wherein *A* stands for permeability coefficient, *S* for the wetted surface area of membrane and NDP for the net driving pressure of the RO process. The term NDP is expressed by (2); wherein, p_{appl} stands for the applied feed pressure at the inlet to head element, Δp for the concentrate side pressure drop, p_p for permeate pressure and p_π for the average osmotic pressure. In light of (1) and (2) Q_p may be expressed by (3) and p_{appl} either by (4A) as a function of Q_p or by (4B) as a function of flux (*F*). The basic power equation of PFD (5A) is expressed (kW) as a function of Q_f (m^3/h) and p_{appl} (bar); wherein, *f* stands for the efficiency factor of the pressurizing pump, as well as by (5B) also in relationship to the permeate flow Q_p (m^3/h) or by (5C) also in relationship to flux (m^3/h/m^2 membrane surface). Units in the power and energy equations considered hereinafter are the same as 5(A–C). The basic SE equation without ER from brine which accounts for feed flow (Q_f), permeate flow (Q_p), applied pressure (p_{appl}) and efficiency of pump (*f*) is expressed by (6A), and in relationships to applied pressure (p_{appl}) and recovery (*R*) by (6B). The basic SE equations with ER from brine (SE$_{ER}$) which account for the same parameters as in (6A) and (6B) as well as for the *absolute energy conversion coefficient* of the entire process (μ_{EC}) is expressed by (7A) and (7B), respectively. It is important to note that μ_{EC} takes into account the energy conversion efficiency of the ER device as well as of the other losses in the system such as for example Δp. In simple terms, the efficiency conversions coefficient μ_{EC} takes account of all the fractions of the recovered energy out of the absolute amount of the "extra energy" derived from the excess flow ($Q_f - Q_p$) of pressurized feed at the inlet to modules; thereby, provides a uniformed unbiased model to establish an absolute energy conversion efficiency irrespective of the efficiency of a specific ER device. Nonetheless, it is obvious that an ER device of exceptionally high efficiency should lead to high μ_{EC} coefficient and vice versa. The term "extra energy" stands for the fraction $(Q_f - Q_p)/Q_f$ of the pumped energy at inlet to RO modules and μ_{EC} reflects the fraction of the "extra energy" actually recovered from the none productive flow at inlet.

The absolute energy conversion efficiency coefficient terms (μ_{EC}) expressed by (8A) and (8B) are derived from the respective SE equations (7A) and (7B).

In light of rising energy costs worldwide and since seawater reverse osmosis (SWRO) consumes considerable amounts of energy, the absolute term μ_{EC} becomes an important feature for the selection of a suitable ER technology in order to attain maximum energy efficiency in such processes. The evaluation of μ_{EC} may rely on real performance data of SE, *R* and p_{appl} according to (8B) or on reliable projected data made available by computerized design program of membrane manufacturers.

$$Q_p = A \times S \times \text{NDP} \tag{1}$$

$$\text{NDP} = p_{appl} - \Delta p/2 - p_p - p_\pi \tag{2}$$

$$Q_p = A \times S \times (p_{appl} - \Delta p/2 - p_p - p_\pi) \quad (3)$$

$$p_{appl} = Q_p/A/S + \Delta p/2 + p_p + p_\pi \quad (4A)$$

$$p_{appl} = F/A + \Delta p/2 + p_p + p_\pi \quad (4B)$$

$$P\ (\mathrm{kW}) = Q_f \times p_{appl}/36/f \quad (5A)$$

$$P(\mathrm{kW}) = Q_f \times (Q_p/A/S + \Delta p/2 + p_p + p_\pi)/36/f \quad (5B)$$

$$P(\mathrm{kW}) = Q_f \times (F/A + \Delta p/2 + p_p + p_\pi)/36/f \quad (5C)$$

$$\mathrm{SE}\ (\mathrm{kWh/m^3}) = Q_f/Q_p \times p_{appl}/36/f \quad (6A)$$

$$\mathrm{SE}\ (\mathrm{kWh/m^3}) = 100/R \times p_{appl}/36/f \quad (6B)$$

$$\mathrm{SE_{ER}}(\mathrm{kWh/m^3}) = [Q_f/Qp \times p_{appl}/36/f] \times [1 - \mu_{EC} \times (1 - R/100)] \quad (7A)$$

$$\mathrm{SE_{ER}}(\mathrm{kWh/m^3}) = [100/R \times p_{appl}/36/f] \times [1 - \mu_{EC} \times (1 - R/100)] \quad (7B)$$

$$\mu_{EC} = \{1 - \mathrm{SE_{ER}}/(Q_f/Q_p \times p_{appl}/36/f)\}/(1 - R/100) \quad (8A)$$

$$\mu_{EC} = \{1 - \mathrm{SE_{ER}}/(100/R \times p_{appl}/36/f)\}/(1 - R/100) \quad (8B)$$

In conventional PFD technology, permeate quality of a new membrane at 25 °C in the absence of FFs is expressed by (9); wherein, C_p stand for permeate concentration, B for salt diffusion coefficient, C_{fc} for feed average concentration and pf for a concentration polarization factor which accounts for recovery, or alternatively by (10) as a function of flux (F).

$$C_p = B \times C_{fc} \times pf \times S/Q_p \quad (9)$$

$$C_p = B/F \times C_{fc} \times pf \quad (10)$$

The SE of conventional PFD is expressed by (6A) and (6B) without ER and by (7A) and (7B) with ER means, irrespective of their exact type, with absolute energy conversion coefficient (μ_{EC}) expressed in (8A) and (8B). A theoretical approach to assess the absolute energy conversion efficiency of seawater desalination is exemplified for Mediterranean Water (salinity of 4.05%) in Table 1 and Fig. 1 with respect to reported [3] performance of the large SWRO desalination plant in Palmachim Israel which operates at 46% recovery and flux of 13–14 lmh at 25 °C with RO feed pressure of 63 bar and high pressure (HP) pump efficiency of around 85%. The total RO energy consumption of the said plant in the absence of ER is 4.476 kWh/m^3 of which 2.059 kWh/m^3 is associated with permeate production and 2.417 kWh/m^3 with wasted brine energy.

The specific RO energy consumption in such plants depends on the type of membrane elements, the average flux, the efficiency of the HP pump and other parameters which are accounted for by the applied pressure (p_{appl}) expressions (4A) and (4B) as well as by the recovery expression in (6B). The reference specific energy ($\mathrm{SE_{ref}}$) column in Table 1 simulates a plausible range of monitored energies, the difference $\mathrm{SE_{ref}}$–$\mathrm{SE_p}$ manifests the so-called “extra energy” at each said reference point, and said difference in relationship to the theoretical maximum term $\mathrm{SE_b}$ provides the absolute energy conversions efficiency term at each reference point. The column of percent absolute ER from brine energy in Table 1 exemplifies the meaning of the absolute energy conversion efficiency coefficient μ_{EC} expressed by (8B). Absolute energy conversion efficiency of 85, 90 and 95% under the operation conditions specified for the SWRO Palmachim plant should have led to the respective SE values 2.47, 2.30 and 2.18 kWh/m^3; whereas, the reported [3] energy value of 2.70 kWh/m^3 attained with the ERT-PX HYBRID ER device stands for an absolute energy conversion efficiency of 73.5% according to the data in Table 1 and the energy value of 2.95 kWh/m^3 reported [3] when the same plant utilizes only the ERT-Pelton device corresponds to an absolute energy conversion efficiency of only 63%. The reported [3] Palmachim performance makes reference to net energy transfer efficiency “just over 76% at the best efficiency point”; and therefore, is fully consistent with the analysis provided in Table 1.

The RO energy reported for the other large desalination plants in Israel including the SWRO-DWEER Ashkelon (2.98 kWh/m^3) [4], the SWR0-PX Hadera (2.73 kWh/m^3) [5] and the SWRO-DWEER Soreq (2.65 kWh/m^3) [5] reveals the respective absolute energy conversion efficiencies of 62, 67 and 76%, assuming that said plants are operated under similar flux, pressure, recovery and temperature conditions as those reported for Palmachim.

The theoretical approach to assess the absolute energy conversion efficiency of Ocean SWRO desalination plants was also examined in Table 2 and Fig. 2 with respect to the reported [6] information for the SWR0-PX plant in Perth Australia (3.4%; 2.47 kWh/m^3; 63.8 bar; 45% recovery; HP-Eff. 86% at temperature of

Table 1
SWRO Palmachim[3]—mediterranean seawater (4.05%) at 25 °C

Reported parameters[a]			SE cosntituents[b]			Reference SE_{ref} kWh/m^3	$\Delta SE^c = SE_{ref} - SE_p$ kWh/m^3	Brine[d] ER %	Calculated (8B) μ_{ER}
REC %	p_{appl} bar	HP-Eff. ratio	SE_{total} KWh/m^3	SE_P kWh/m^3	SE_b kWh/m^3				
46	63	0.85	4.476	2.059	2.417	3.00	0.94	61.06	0.6106
46	63	0.85	4.476	2.059	2.417	2.95	0.89	63.13	0.6313
46	63	0.85	4.476	2.059	2.417	2.90	0.84	65.20	0.6520
46	63	0.85	4.476	2.059	2.417	2.85	0.79	67.26	0.6726
46	63	0.85	4.476	2.059	2.417	2.80	0.74	69.33	0.6933
46	63	0.85	4.476	2.059	2.417	2.75	0.69	71.40	0.7140
46	63	0.85	4.476	2.059	2.417	2.70	0.64	73.47	0.7347
46	63	0.85	4.476	2.059	2.417	2.65	0.59	75.54	0.7554
46	63	0.85	4.476	2.059	2.417	2.60	0.54	77.61	0.7761
46	63	0.85	4.476	2.059	2.417	2.55	0.49	79.68	0.7968
46	63	0.85	4.476	2.059	2.417	2.50	0.44	81.75	0.8175
46	63	0.85	4.476	2.059	2.417	2.45	0.39	83.81	0.8381
46	63	0.85	4.476	2.059	2.417	2.40	0.34	85.88	0.8588
46	63	0.85	4.476	2.059	2.417	2.35	0.29	87.95	0.8795
46	63	0.85	4.476	2.059	2.417	2.30	0.24	90.02	0.9002
46	63	0.85	4.476	2.059	2.417	2.25	0.19	92.09	0.9209
46	63	0.85	4.476	2.059	2.417	2.20	0.14	94.16	0.9416
46	63	0.85	4.476	2.059	2.417	2.15	0.09	96.23	0.9623
46	63	0.85	4.476	2.059	2.417	2.10	0.04	98.30	0.9830

[a] The data are for flux of 13–14 lmh with membranes type TORAY 820 C.

[b] Total according to feed flow-pressure and constituents (permeate and brine) by recovery.

[c] ΔSE is the theoretical SE_b at the reference energy SE_{ref}.

[d] % Energy conversion efficiency [$=(1 - \Delta SE/SE_b) \times 100$] at the reference energy SE_{ref}.

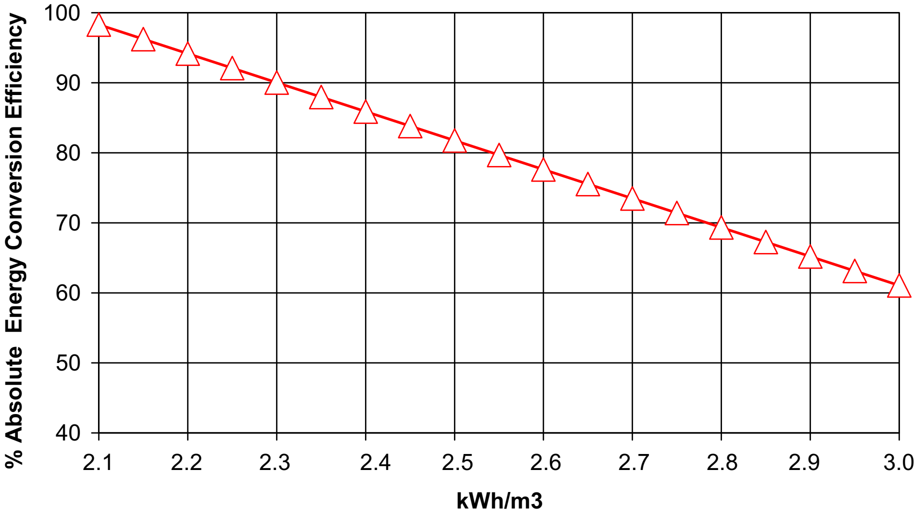


Fig. 1. Specific energy vs. % absolute energy conversion efficiency for SWARO Palmachin (4.05%; 46% recovery; 63 bar; 85% HP-Eff; 25 °C).

25 °C). Absolute energy conversion efficiency of 85, 90 and 95% under the operation conditions specified for the SWRO-PX Perth plant should reflect the respective SE values 2.43; 2.30 and 2.17 kWh/m^3; and therefore, the reported[6] value of 2.47 kWh/m^3 for this plant corresponds to an absolute energy conversion efficiency of about 83%. In contrast with the energy efficient plant in Perth, the Ocean Seawater SWRO-DWEER plant in Tuas Singapore was reported [5] to operate with SE of 3.11 kWh/m^3 which according to Table 2 implies an absolute energy conversion efficiency under 60%, provided that both Tuas and Perth plants are operated under similar conditions.

ER in conventional SWRO desalination processes is a vital part of the technology and the various devices conceived and developed for this purpose are extensively reviewed in the literature, nevertheless, the effectiveness of such devices can be judged objectively only on the basis of an entire plant energy performance instead of the performance of an isolated device. The absolute energy conversion efficiency approach considers the energy performance of the entire desalination system irrespective of a specific ER device. In simple terms, the absolute energy conversion efficiency criteria takes account not only of the specific ER device but also of its effective integration in the entire system which comprises many other components. The reliability of the absolute energy conversion efficiency criteria depends on the accuracy of the available data of energy consumption, pressure of operation, recovery, efficiency of pumps and temperature and such data originating from the operation of large and efficient desalination plants is generally considered unbiased and reliable.

3. New CCD technology

In contrast to the widespread conventional RO, the terms CCD or "Closed Loop Desalination" originated in the patent literature [7–9] for a rare class of batch RO processes of little if any commercial prospects until recently. The CCD batch technology which operates under hydrostatic conditions is illustrated schematically in Fig. 3 by a unit comprising pressure vessel with a semi-permeable membrane separation between the pressurized feed section and the permeate section. Pressurized feed is supplied by a HP pump equipped with variable frequency drive (*vfd*) to enable fixed flow and variable pressure operation and a stirring device (SD) is placed inside the pressurized section of the vessel to enable the disruption of the salt layer created over the membrane surfaces during the desalination process; thus, reduced the concentration polarization effect which inhibits desalination. If operated under fixed flow and variable pressure conditions, the initiation of the batch starts with fresh feed and concludes at a desired level of concentrate salinity, or applied pressure, when it reaches the desired desalination recovery level; thereafter, the process stops, the container is decompressed and brine is replaced by fresh feed before a new batch of desalination sequence is initiated. The volume of fresh feed compressed into the pressurized vessel during batch desalination is identical to the volume of permeate released at near atmospheric pressure, and therefore,

Table 2
SWRO Perth[6]—ocean seawater (3.40%) at 25 °C

Reported parameters[a]			SE cosntituents[b]			Reference SE_{ref} kWh/ m3	$\Delta SE^{c} = SE_{ref} - SE_{p}$ kWh/m3	Brine[d] ER %	Calculated (8B) μ_{EC}
REC %	p_{appl} bat	HP-Eff. ratio	SE_{total} kWh/m3	SE_{P} KWh/m3	SE_{b} kWh/m3				
45	63.8	0.86	4.579	2.061	2.519	3.05	0.99	60.72	60.72
45	63.8	0.86	4.579	2.061	2.519	3.00	0.94	62.71	62.71
45	63.8	0.86	4.579	2.061	2.519	2.95	0.89	64.69	64.69
45	63.8	0.86	4.579	2.061	2.519	2.90	0.84	66.68	66.68
45	63.8	0.86	4.579	2.061	2.519	2.85	0.79	68.66	68.66
45	63.8	0.86	4.579	2.061	2.519	2.80	0.74	70.65	70.65
45	63.8	0.86	4.579	2.061	2.519	2.75	0.69	72.63	72.63
45	63.8	0.86	4.579	2.061	2.519	2.70	0.64	74.62	74.62
45	63.8	0.86	4.579	2.061	2.519	2.65	0.59	76.60	76.60
45	63.8	0.86	4.579	2.061	2.519	2.60	0.54	78.59	78.59
45	63.8	0.86	4.579	2.061	2.519	2.55	0.49	80.57	80.57
45	63.8	0.86	4.579	2.061	2.519	2.50	0.44	82.56	82.56
45	63.8	0.86	4.579	2.061	2.519	2.45	0.39	84.54	84.54
45	63.8	0.86	4.579	2.061	2.519	2.40	0.34	86.53	86.53
45	63.8	0.86	4.579	2.061	2.519	2.35	0.29	88.51	88.51
45	63.8	0.86	4.579	2.061	2.519	2.30	0.24	90.50	90.50
45	63.8	0.86	4.579	2.061	2.519	2.25	0.19	92.49	92.49
45	63.8	0.86	4.579	2.061	2.519	2.20	0.14	94.47	94.47
45	63.8	0.86	4.579	2.061	2.519	2.15	0.09	96.46	96.46
45	63.8	0.86	4.579	2.061	2.519	2.10	0.04	98.44	98.44

[a] The data are for flux of 13–14 lmh with membranes type SW30HR-LE400 by Filmtec.

[b] Total according to feed flow-pressure & constituents (permeate & brine) by recovery.

[c] ΔSE is the theoretical SE b at the reference energy SE_{ref}.

[d] % Energy conversion efficiency [$=(1 - \Delta SE/SE_{b}) \times 100$] at the reference energy SE_{ref}.

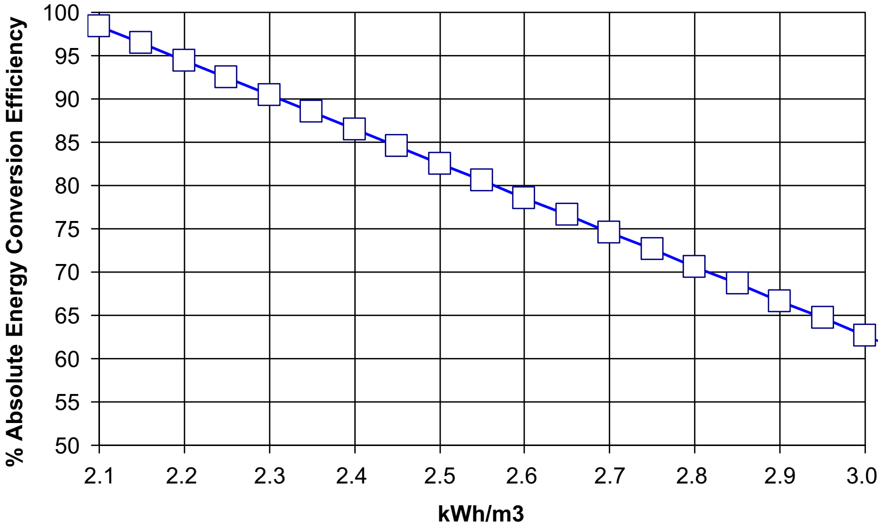


Fig. 2. Specific energy vs % absolute energy conversion efficiency for SWRO Perth (3.5%; 45% Recovery; 63.8 bar; 86% HP-Eff; 25 °C).

this technology is an *absolute energy method* with SE determined only by the average pressure during the batch process which accounts for the initial and final pressures, plus a small energy increment arising from the power needs of the SD. The term "absolute energy" distinguishes between CCD and PFD since the inlet energy demand in the former is only associated with permeate production; whereas, in the latter some of the energy is also required to pressurize the brine. Since pressurized fresh feed is continuously supplied to the batch vessel, change of salinity inside the vessel is more gradual due to the dilution effect which is not possible in conventional PFD.

A batch CCD apparatus with conventional parts and components is illustrated in Fig. 4 with a design comprising a single pressure vessel with three membrane elements inside, a feed pressurizing pump (HP), a circulation pump (CP) for concentrate recycling from outlet to inlet of module(s) as well as for pressure loss compensation (Δp) and combination of a two-way valve (AV) with a check valve (OWV) down stream, or a three-way valve instead, to enable brine replacement with fresh feed when batch desalination completed at a desired recovery level. Batch CCD operates on the basis of hydrostatic principles with same flow rates of pressurized feed and permeate. The cross flow over membranes is created in CCD by circulation means, instead of the excess feed flow requirement of conventional PFD. Batch CCD takes place only in the presence of concentrate recycling, without which desalination stops due to an immediate rise in concentration polarization. Batch CCD operates without the need for ER since the compression and decompression steps of the batch reactor during the respective steps of actuation and terminations involve the loss of *negligible amount* of hydrostatic energy.

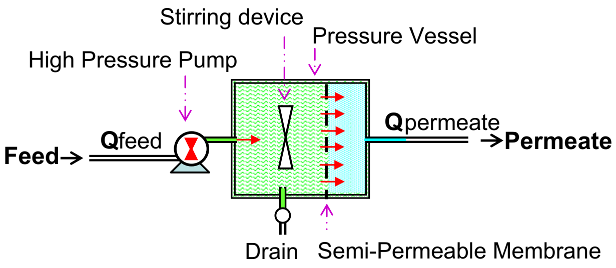
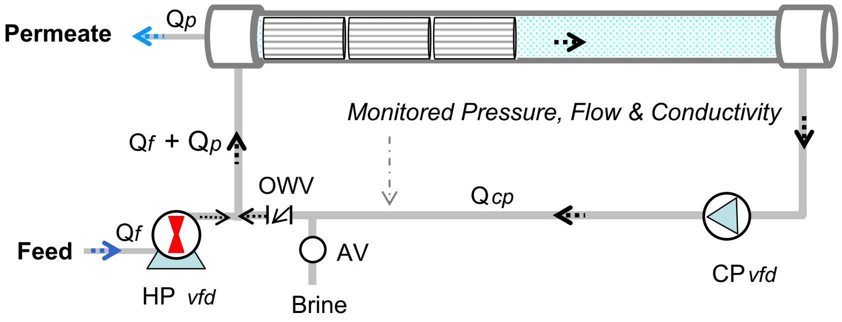


Fig. 3. A simplified reactor for batch desalination in closed circuit.

Batch CCD operates by different rules compared with conventional PFD since batch system recovery (R_S) is expressed by (11); wherein, **V** stands for the fixed intrinsic volume of the batch reactor and **v** for the permeate volume produced during a defined sequence, or the feed volume consumed, during a single batch operation. If batch CCD proceeds with fixed feed flow (Q_f) under variable pressure conditions with average pressure expressed by p_{av}, the volume term v expressed by (12); wherein, T stands for the time of a single batch sequence duration. Substituting **v** in (11) from its expression in (12) gives (13) which establishes the relationships between R_S, T, V and Q_f ($=Q_p$). The module recovery (MR) of the unit displayed in Fig. 3 is expressed by (14) and this term is fully dependent on the flow rates of HP (Q_f) and CP (Q_{CP}) and the same is also true for the head element recovery (HER)



HP *vfd* - Feed pressurizing Pump with a variable frequency drive
CP *vfd* - Circulation Pump with a variable frequency drive
AV — Two-way actuated Valve
OWV — One way check valve

Fig. 4. A schematic design of an apparatus for batch CCD with conventional components comprising one module with three membrane elements.

which is a function of MR. The SE terms of a Batch CCD process are expressed by (15) and (16) for HP and CP, respectively, with total RO energy demand expressed by the sum of the two terms; wherein, f_{HP} and f_{CP} stand for the efficiency factors of the respective pumps.

$$R_s\% = [v/(v+V)]\times 100 \tag{11}$$

$$v = Q_f\times T = Q_p \times T \quad \text{Since } Q_f = Q_p \tag{12}$$

$$\begin{aligned} T &= R_s \times V/[Q_f \times (100 - R_s)] \\ &= R_s\times V/[Q_p\times(100 - R_s)] \end{aligned} \tag{13}$$

$$\begin{aligned} \text{MR } (\%) &= Q_f\times 100/(Q_f + Q_{CP}) \\ &= Q_p\times 100/(Q_p + Q_{CP}) \end{aligned} \tag{14}$$

$$\text{SE}_{\text{HP}} = p_{av}/36/f_{\text{HP}} \tag{15}$$

$$\text{SE}_{\text{CP}} = Q_{\text{CP}}\times \Delta p/36/f_{\text{CP}}/Q_p \tag{16}$$

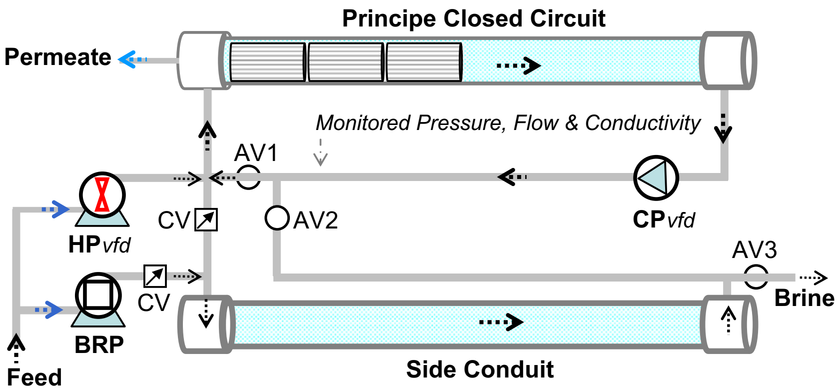
In contrast to conventional PFD, batch CCD is a *Multiple-Modes Technology* of enormous flexibility which enables to operate with fixed feed flow under variable pressure conditions, or with fixed permeate flow under variable pressure conditions or under fixed pressure and variable flow conditions, with the former two alternatives preferred due to constant NDP which implies little if any motion of the membranes surfaces. CCD operation under fixed flow and variable pressure conditions enables to select the flux (F) and all flow parameters (Q_f, Q_p, Q_{CP}); thereby, to dictate the performance of the membranes (MR and HER) without exceeding the performance specifications of their manufacturers. System recovery (R_S) in CCD is unrelated to MR and/or to the number of elements per module, and depends primarily on the duration of the batch sequence and is determined by the salinity of the recycled concentrate and/or by the applied pressured at the desired system recovery level. The low energy consumption in batch CCD achieved without the need of ER and with small pressurizing means. Batch CCD is a low fouling (bio and particulate matter) technology due to use of short modules (2–4 elements each) which eliminate tail element effects of conventional technology vessel configurations; large salinity variations of recycled concentrate, fast cross flow over membranes surfaces and frequent replacement of the entire brine in the system by fresh feed.

In general, batch processes are unattractive for large-scale commercial applications and the same is also true for CCD. Conversion of batch CCD into a viable commercial technology requires such process to operate continuously with respect to permeate production by simple means and such a development is described next. The first method [10] for the making of batch CCD continuous with respect to permeate production under fixed flow and variable pressure conditions is illustrated with the apparatus of the schematic design in Fig. 5. comprising a single module of three elements and a side conduit (SC) of the same intrinsic volume which can be either engaged with or disengaged from the principle closed circuit (PCC) by means of the actuated valves AV1 and AV2 with an added valve AV3 to enable the replacement of brine by fresh feed in the SC at near atmospheric pressure with a negligible loss of brine energy. The PCC section displayed in Fig. 5. operates CCD under fixed flow and variable pressure conditions while the disengaged SC is being charged with fresh feed at near atmospheric pressure (AV1 and AV3 opened and AV2 closed); thereafter, the SC with fresh feed is sealed and compressed just before the next engagement takes place when the desired system recovery is attained.

Reaching the desired recovery level in the PCC is determined by monitoring the applied pressure and/or salinity (or Electric Conductivity [EC]) of the recycled concentrate. When the desired system recovery is reached, the pressurized SC is engaged with the PCC (AV1 and AV3 closed and AV2 opened) to enable brine replacement by fresh pressurized feed without stopping desalination which proceeds with an unaffected flow of permeate production. The engagement is terminated (AV1 open and AV2 closed) by a volume metre signal after the desired volume of brine is replaced by fresh pressurized feed in the PCC. After disengagement, the SC is decompressed (AV3 opened), the brine replacement pump (BRP) is actuated to enable replacement of brine by fresh feed in the SC, then the BRP is stopped, and the SC full with fresh feed is sealed and awaits the next engagement.

The consecutive sequential technology is illustrated in Fig. 5 for a single-module unit with three elements (ME3) and this modular technology may apply to any *NxMEn* design combination; wherein, *N* stands for the number of modules in the configuration with their inlets and outlets connected in parallel, and *n* for the number of membrane elements per module. A unit with 8xME4 (*E* = ESPA2+) design of the CCD technology with SC [10] has been operated continuously over the past 2.5 years and reported elsewhere [11]. The tested unit operated at RO system recovery of 80% with a feed of 6,800 μS/cm, under constant permeate flow (24.4 m^3/h; 19 lmh) and variable pressure conditions (11→22 bar; average 17.7 bar; $\Delta = 0.75$ bar). The average permeate quality produced by the CCD unit was 625 μS/cm and the average RO energy consumption was 0.82 kWh/m^3 with HP pump efficiency of ∼55%. The same unit was also operated briefly (44 h) with a feed source of 4,000 μS/cm at 88% system recovery and fixed permeate flow (35.0 m^3/h; 27 lmh) under variable pressure conditions (12→21 bar; average 16.2 bar) with average permeate quality of 882 μS/cm and an overall RO energy consumption of 0.80 kWh/m^3 with HP pump efficiency of ∼60%. The fully automated 8xME4 (*E* = ESPA2+) unit under review is operated commercially by remote control with infrequent visits to its site and with low membrane cleaning frequency in spite of the difficult source of water quality, part of which includes domestic and/or industrial effluents.

The application of the CCD technology [10] for seawater desalination (SWRP-CCD) was carried out initially with a unit of the 4xME4 (*E* = SWC6) design with Mediterranean seawater salinity of 4.05 ± 0.5% at 22.5 ± 0.5 °C. The system was operated at a recovery of 47.0 ± 1.5% and the reported results [12] revealed exceptional low RO energy consumption *without the need of ER* of 1.85–2.25 kWh/m^3 in the respective flux range 8→17 lmh with a mean HP efficiency of 82 ± 2% and a mean CP efficiency of 25 ± 5%. The sequential average pressure rise during these trials (average



HP *vfd* - Feed Pressurizing Pump with a variable frequency drive
CP *vfd* - Circulation Pump with a variable frequency drive
BRP - Brine Replacement Pump
AV — Two-way actuated Valve

Fig. 5. A schematic design of an apparatus for continuous CCD with conventional components comprising one module with three membrane elements.

pressure: 51→57 bar; average Δp: 0.25→1.05 bar) was found to be proportional to the flux; whereas, permeate average electric conductivity (EC: 640→480 µS/cm) was found to be inversely proportional to the flux. During the reported [12] trials of the consecutive sequential SWRO-CCD system under review, MR was maintained at 22 ± 2% with HER of 7.0 + 0.5%. In the flux range of 8→17 lmh, the RO energies during the Mediterranean seawater (salinity of 4.05%) trials normalized to 85% efficiency of HP and 60% efficiency of CP were found in the respective range of 1.65→1.90 kWh/m^3 and with an extrapolated respective range of 1.50→1.75 kWh/m^3 for ocean seawater (3.5%). Never before such results were reported for commercially operated plants anywhere by a source not affiliated with the ER industry.

The 4xME4 (E = SWC6) unit under review was located in the backyard of the full-scale Palmachim plant in Israel and used the same feed water. The comparative trials of the CCD unit with the large Palmachim plant, which were carried out with the exact same feed salinity (54,200 µS/cm) and temperature (30.1 °C) under the same flux (12.77 lmh) conditions, revealed for CCD an average RO specific energy of 2.26 kWh/m^3 for 48.0 ± 1.5% recovery and ~80% HP efficiency, or 1.96 kWh/m^3 if value corrected to 25 °C. The energy consumption of the full-scale Palmachim plant under similar recovery and flux conditions was reported [3] to be 2.95 kWh/m^3 with ERT-PELTON and 2.70 kWh/m^3 with an ERT-PX hybrid system. RO energy consumption under 2.7 kWh/m^3 has never been reported for any of the large-scale desalination plants in Israel irrespective of the type of membrane elements and/or ER devices used, and this implies that the better energy efficiency of the CCD is due to the principle differences between PFD and CCD technologies rather than the differences in RO elements and/or ER devices.

The flexibility of the new CCD Technology as applied to Mediterranean seawater is also demonstrated by the reported[13] extensive trials over a wide flux range (8→40 lmh) using the apparatus 4xMEn (E = SWC6) configurations $n = 1→4$ in the respective ranges 3→10 m^3/h for HP feed and/or permeate; 15→55 m^3/h for CP recycling and 60→75 bar for maximum sequential pressure. MR in these trials was selected according to module configuration as follows: 22 ± 2% (ME4); 19 ± 2% (ME3); 15 ± 1% (ME2); and 9 ± 3% (ME). The HER during these trials was selected in the range of 6 ± 2% for the 4xMEn (n = 2–4) apparatus configurations and 9 ± 3% for the 4ME configuration. The reported [13] trials with the 4xME2 configuration apparatus were carried out at temperatures of 30.0 ± 1.0 °C; whereas, the remaining trials at 25.0 ± 1.5 °C. RO energies, without temperature corrections, observed during these trials were in the range of 1.8→2.8 kWh/m^3 for the respective flux range 8–40 lmh and system recovery up to 50%. Mediterranean CCD trials RO energy in the flux range (13–14 lmh), characteristic of the large conventional SWRO plants in Israel, was found in the range 1.9–2.2 kWh/m^3 with a plausible further improvement to 1.7–1.8 kWh/m^3 expected if efficiency of HP and CP increased to 85 and 60%, respectively, with an extrapolated respective range of 1.50→1.75 kWh/m^3 for ocean seawater (3.5%). It is important to note that the entire CCD technology concept originated from theoretical considerations with the aid of computer simulations, and the experimental results fully confirmed the accuracy of the theoretical predictions. Very recently, it was reported [14] that energy consumption requirements of SWRO-CCD can be predicted with an iterative calculation using standard projection software from membrane manufacturers combined with information on pumps, membranes and feed sources salinity and constituents. Moreover, the state-of-the-art RO energy consumption reported hereinabove in the context of SWRO-CCD was never before realized in large and modern commercial seawater desalination plants which are noted for their high efficiency.

Apart from the CCD technology [10] for seawater desalination, new CCD innovations [15,16] were also conceived, developed and implemented specifically for high recovery, low energy and reduced fouling desalination of brackish water. Noteworthy in this context is the reported [17] performance of the commercial 10xME4 (E = ESPA2+) unit at the REIM site in Israel which has been operated continuously during the past two years with 80–88% recovery as a function of the respective feed source salinity variations of 5,800→8,900 µS/cm. This technology utilizes the principle of a modified Fig. 4 design to enable a two-mode consecutive sequential process which incorporates CCD and PFD. Most of the time the system executes CCD and at the desired recovery level, determined by monitored EC of recycled concentrate and/or by applied pressure, the entire brine in the system is replaced by fresh feed with PFD, and thereafter, CCD resumed. The fully automated 10xME4 (E = ESPA2+) REIM unit under review is operated commercially with great flexibility by remote control with low fouling and extended periods between CIP procedures, this in spite of the difficult origin of its source, part of which includes domestic and/or industrial effluents.

The newly conceived CCD-PFD technology [15] is of considerable commercial promise for many high-recovery low-fouling applications in which high flux could effect the production of better quality permeates (e.g. one-step production of permeates of low salinity—under 10 ppm) and/or enable more effective removal of certain undesired constituents such as nitrate in contaminated drinking water and/or boron in a second pass of seawater permeates. The aforementioned technology is exemplified with the recently reported [18] use of the ME3 (E = RE8040-BE440) CCD-PFD unit in the flux range 33–37 lmh for nitrate decontamination of feed with 98, 144 and 197 ppm NO_3 to the respective permeates of 19, 27 and 44 ppm NO_3 with 90% recovery at 20 °C. The results obtained meet the requirement [19] in the USA and Canada (maximum: 44.3 ppm NO_3) as well as by WHO [20] (maximum: 50 ppm NO_3). Nitrate decontamination is an increasing problem worldwide and expensive EDR apparatus are extensively used for this purpose with minor emphasis given thus far to conventional RO which was considered inferior. The high flux and high recovery CCD-PFD technology [18] opened the door for intensive use of advance RO instead of EDR for this application, with equivalent or better results and with considerable savings of installation costs and running expenses.

Another noteworthy application of the CCD is the so-called "Retrofit" technology [16] for improved performance of common RO system; whereby, the pressurized brine of a conventional RO system is admitted into a CCD unit of the type displayed in Fig. 5. through a fixed flow variable pressure booster pump for further desalination of the brine to the desired recovery level under controlled conditions of low scaling and fouling (bio- and particulate matter) characteristics. The first commercial unit [21] on the basis of this technology for 55 m^3/h starting with feed of 6,000–6,700 μS/cm comprises the first conventional stage of 5xME5 PFD array of 50% recovery with its entire pressurized brine admitted into a 7xME4 CCD unit, wherein, the recovery of the entire system raised to 86–88% with an overall RO energy consumption of 0.57 kWh/m^3.

4. Comparison of conventional PFD with CCD

The comparison is according to subject matter and focuses on seawater desalination with clear reference to brackish water whenever appropriate:

4.1. Technology characteristics

4.1.1. PFD

A single-mode, continuous hydrodynamic process performed with fixed pressurized feed flow (Q_f) at the inlet of an apparatus which splits at outlet into un pressurized permeate flow (Q_p) and pressurized brine flow (Q_b); with flow balance expressed as $Q_f = Q_p + Q_b$; recovery expressed by $Q_p/Q_f \times 100$ and depends on the number (n) of membrane elements arranged in line inside the pressure vessel (MEn) and their performance specifications, and with a minimum flow ratio Q_p/Q_b requirement per each element to enable a sufficiently low concentration polarization effect.

4.1.2. CCD

A multiple-mode hydrostatic batch process in a confined intrinsic volume (V) performed with fixed pressurized feed flow (Q_f) under variable pressure conditions by concentrate recycling (Q_{CP}) combined with fresh feed mixing in short modules (MEn; n = 1–4); made continuous with respect to permeate production by occasional engagement of a SC of the same intrinsic volume; whereby, brine is replaced by fresh feed without stopping desalination. The main operational set points of this consecutive sequential process are the flow rates Q_f and Q_{CP} which define MR ($Q_f/(Q_f + Q_{CP})$), HER, cross flow over membrane surfaces (Q_{CP}) and minimum permeate/concentrate flow ratio (Q_f/Q_{CP}) as well as the maximum sequential pressure, or maximum electric conductivity of recycled concentrate instead, which define the desired system recovery irrespective of the number of element per module.

4.1.3. Assessment

Conceptually different methods of different performance characteristics and of different control means.

4.2. Design and performance flexibility

4.2.1. PFD

Fixed design for desired flow, flux and recovery of specific membrane elements and a fixed number of elements per module with limited performance variability.

4.2.2. CCD

Flexible design of infinite performance variations as results of independent control set points of feed flow, permeate flow, cross flow, flux, MR, HER and system recovery irrespective of number or type of the elements per module.

4.2.3. Assessment

CCD offers significant performance flexibility unattainable by conventional PFD.

4.3. Energy consumption

4.3.1. PFD

RO energy consumption dictated by the fixed pressurized feed flow at the inlet of modules for the desired recovery over the specified number of membrane elements per module, combined with the efficiency of ER means from pressurized brine and the efficiency or the feed pressurizing means. The fixed power demand at inlet needs to accommodate the low efficiency performance of the tail elements as well as the overburden of head elements to enable attainment of sufficiently high system recovery. Obviously, attainment of high energy efficiency with such a technology wherein $Q_f = Q_p + Q_b$ greatly depends on the effectiveness of ER from the pressurized brine.

4.3.2. CCD

RO energy consumption depends primarily on the average consecutive sequential pressure since $Q_f = Q_p$ with a small increment due to the recycling pump ($Q_{CP} = Q_b$) which compensates for the pressure drop in modules (Δp: 0.7 ± 0.3 bar, depending on the number of elements per module) and provides sufficient cross flow to minimize concentration polarization effects. The aforementioned facts imply an *absolute energy efficienct* technology which entirely circumvents the need for ER from brine.

4.3.3. Assessment

CCD is a low RO energy consumption technology of high efficiency without the need of ER and its performance is best illustrated by comparison with results reported for large modern conventional SWRO plants with the best ER means (e.g. ERT-PELTON, PX and DWEER) which normally operate at a flux of 13–14 lmh with $47 \pm 2\%$ recovery. The monitored CCD RO energy for Mediterranean water ($4.05 \pm 0.05\%$) under said conditions was 2.08 kWh/m^3 with a normalized (25 °C; 85% eff. HP and 60% eff. CP) value of 1.80 kWh/m^3 for Mediterranean water and a normalized projected value of 1.65 kWh/m^3 for ocean water (3.5%). In comparison, reported RO energy consumptions of the large and modern Mediterranean desalination plants are 2.73 kWh/m^3 for SWRO-PX in Hadera-Israel [5]; 2.98 kWh/m^3 for SWRO-DWEER in Ashkelon-Israel [4]; 2.95 kWh/m^3 for SWRO-PELTON or 2.70 kWh/m^3 for PELTON-PX HYBRID in Palmachim-Israel [3]; and 2.65 kWh/m^3 projected for SWRO-DWEER in Soreq-Israel [5]. The reported RO energy consumption of the large and modern ocean seawater desalination plants is 2.47 kWh/m^3 for SWRO-PX in Perth-Australia (34,000 ppm) [6] and 3.11 kWh/m^3 for SWRO-DWEER in Tuas-Singapore (max. 35,000 ppm) [5]. The large differences in energy consumption between CCD and PFD could not be explained solely on the basis of the ER efficiency from brine in the latter, and most probably reflects the fundamentally different principles of design and operation of these technologies. The energy benefits of CCD compared with PFD, apart from the ER needs by the latter, most probably arise from the fixed flow variable pressure CCD operation with exact required power supplied at each point during the consecutive sequential process; shorter CCD modules of lower pressure difference (lower Δp); CCD dilution effect due to recycled concentrate mixing with fresh feed at the inlet of modules in contrast with sharply increased salinity without dilution along the recovery line of joint membrane elements in PFD; and the highly optimized CCD process with respect to MR, HER and cross flow of low concentration polarization made possible by its flexible operational modes. The subject matter pertaining to efficiency of ER means in PFD and their effect on RO energy have been extensively dealt with over the past decade especially by the affiliates of ER industry—this subject matter is of no interest whatsoever from the standpoint of CCD which circumvents entirely the need for ER. CCD is a technology of conduits and valves and its SC is not an ER device in the absence of pressurized brine flow from which energy needs to be recovered. Moreover, the CCD technology makes use of the same circulation flow (Q_{CP}) to compensate for Δp (0.75 ± 0.3 bar) and control concentration polarization, irrespective of whether the SC is engaged or disengaged. Incidentally, stop of circulation flow (Q_{CP}) in CCD effect an immediate sharp rise in applied pressure requirements and causes termination of desalination due to undesired rise in concentration polarization.

4.4. Performance of membranes and elements

4.4.1. PFD

Operated with fixed NDP per membrane element with entire performance (flow, flux, permeate quality and recovery) dictated by the pressurized feed flow at the inlet of head element and the length of module with decreased desalination efficiency downstream due to increased salinity as well as decreased flow and pressure. Attainment of 47 ± 2% recovery by conventional SWRO, even at a relatively low average flux of 13–14 lmh, requires operating with HER of 12–13% instead of the test conditions (TC) maximum recovery of 10% specified by membrane manufacturers and this is done by increased pressure and power demand. In simple terms, conventional commercial SWRO plants exceed TC specifications of head elements in order to allow for a reasonable recovery.

4.4.2. CCD

Module recovery and HER are completely controlled by the set points selection of Q_f and Q_{CP}; whereas, system recovery determined independently by the set point selection of maximum sequential pressure, or maximum electric conductivity of recycled concentrate instead. In simple terms, performance of membranes and elements within TC specifications is enabled by the set points selection of flow; whereas, system recovery is independently achieved through the controlled set points of pressure and/or salinity.

4.4.3. Assessment

In contrast to conventional SWRO, CCD enables performance at higher flux and system recovery without exceeding TC specifications of manufacturers. For instance, CCD of 50% recovery with short modules (ME3/4) operated in the average flux range 20–26 lmh without exceeding TC specifications will save 35–50% of the elements used by conventional technology and enable improved quality permeates of reduced boron content with a reasonable energy consumption. The same high flux CCD unit could be made to operate at half the flux without exceeding membranes specifications with significant savings of energy, if equipped with a positive displacement pressurizing pump and this versatility and flexibility are unmatched by any conventional technology. The aforementioned implies that existing membranes when operated in the context of the CCD technology render improved performance without exceeding their TC specifications with respect to either increased productivity concomitant with increased flux or decreased energy consumption concomitant with decreased flux. It is important to note that the reported [13,14] performance results of the Mediterranean seawater CCD trials in the flux range 20–26 lmh did not reveal any noticeable fouling effects, and therefore, the aforementioned assessment is realistic rather than a speculation.

4.5. Scaling and Fouling factors of membrane elements

4.5.1. PFD

Scaling and fouling factors enhanced with increased recovery through long modules of many lined elements due to downstream decay of flow, flux and pressure with cumulative results of typical impact to the so-called tail elements. Front elements, and head elements in particular, are prone to particulate matter and organic fouling especially when performance exceeds TC specifications of manufacturers as is commonly practised in order to increase recovery.

4.5.2. CCD

Short modules of 3–4 elements per module operated with fixed flow at a desired flux under variable pressure conditions with controllable cross flow perform with low scaling and fouling characteristics, especially when the performance of modules and membranes can be optimized online by flow control set points. Bio-fouling due to bacteria growth is of low probability in CCD in light of the controllable cross flow and the large salinity variations of recycled concentrate during the consecutive sequences. Moreover, the recycled concentrate in CCD is mixed with fresh feed at the inlet of modules and the entire brine content in the closed circuit is replaced by fresh feed on a frequent basis at the end of each sequence; therefore, seeds formation which accelerates scaling development is reduced or inhibited. It is important to note that the aforementioned expected characteristics of the CCD technology with regard to scaling and fouling are fully supported by the reported experimental results which apply both to seawater [12,13] and brackish water [11,17,21].

4.5.3. Assessment

Scaling and fouling are one of the most common problems of conventional PFD processes especially with increased recovery BWRO and to a lesser extent with conventional SWRO wherein prevention of biofouling is of some importance. Scaling and fouling problems of increased intensity are encountered in particular with variable salinity feed sources. Scaling and fouling control of commercial RO plants is a major issue of severe economic consequences in light of declined performance, decreased plant availability while stopped for CIP, shorter lifetime of membrane with increased frequency of CIP procedures and finally the inevitable need to replace membranes too frequently at a considerable expense in order to maintain adequate plant performance. Accordingly, the application of a low scaling and fouling technology such as CCD compared with PFD provides significant durable economical benefits well beyond the initial installation stage.

4.6. Components requirements of compared technologies

4.6.1. PFD

Disregarding pre-treatment and post-treatment, installation costs of conventional SWRO units are a function of the number and type of the principle components in their design including membranes, pressure vessels, high-quality stainless steel distribution piping, feed pressurizing means, ER devices as well as monitoring and control means. SWRO plants operated in the flux range 13–15 lmh will require the same number of membranes and pressure vessels irrespective of the of ER device type. The use of ERT (e.g. PELTON) implies the need for feed pressurizing means of $Q_f = Q_p / R \times 100$, or twice the flow rate of permeate and more if recovery is under 50%. In the case of ER means such as PX and DWEER, the principle feed pressurizing means supply the equivalent flow of permeate ($Q_f = Q_p$); whereas, extra pressurized fresh feed at the inlet of modules of $Q_{\text{extra}} = Q_p \times (100 - R)/R$ is supplied by the ER device (hydraulically driven feed pressurizing pump) through a booster pump in order to compensate for the pressure loss (Δp: 2–3 bar). In summary, pressurized feed at inlet to modules is always $Q_f = Q_p / R \times 100$ supplied either by a single pump as in the case of SWRO-ERT or through several pumps including the ER device and a booster pump as in the cases of SWRO-PX and SWRO-DWEER. While the aforementioned is said for conventional SWRO technologies which are generally practised with low recovery in the range 40→50%, the situation with regard to conventional BWRO of 75→90% recovery is somewhat different since attainment of high recovery implies a long line of membranes in staged arrays of pressure vessels with inter-stage boosters or turbo-charges required in order to enable performance with a reasonable energy consumption.

4.6.2. CCD

The principle components in the technology under review include membranes, pressure vessels, a single feed pressurizing pump of $Q_f (= Q_p)$, a concentrate recycling pump $Q_{CP} (\sim 1.5 \times Q_p;\ \Delta p = 0.7 \pm 0.2\,\text{bar})$ as well as monitoring and control means—no ER means are included among the components. The principle CCD technology for seawater is that of SCs [10]; whereas, the preferred technology for brackish water desalination of high recovery and low energy is that of CCD-PFD [15] with the latter step (PFD) implemented occasionally and briefly for the replacement of brine with fresh feed without stopping desalination.

4.6.3. Assessment

CCD is a simple technology of flexible control which makes used of small feed pressuring means, since $Q_f = Q_p$, and enables high recovery with low RO energy without the need of ER by a process of reduced scaling and fouling characteristics—features unattainable by conventional PFD technology. Apart from the mandatory concentrate recycling means for CCD of similar power consumption requirements compared with the booster pumps associated with PX and DWEER, the relatively expensive ER devices with their pressurized conduit lines and control means are completely circumvented by the CCD technology at considerable savings of installation costs. Invariably, the CCD technology enables high recovery by simple means irrespective whether it applies to seawater or brackish water; and therefore, saves on pre-treatment installation costs compared with conventional technology of lower recovery. Moreover, the CCD technology can be operated with higher flux without exceeding membranes specifications; thereby, save on costs of membrane elements and afford better quality permeates of higher commercial value. The conventional SWRO-DWEER technology is practised successfully worldwide in *large desalination plants* with an ER device made of conduits and valves; and therefore, its comparison with CCD is noteworthy in particular. In SWRO-DWEER, the ER hydraulic device compresses part of the fresh feed supply to inlet of modules with a flow rate previously defined as $Q_{\text{extra}} = Q_p \times (100 - R)/R$; whereas, the other part of pressurized feed to the inlet of modules is supplied by means of the principle pressurizing pump with a rate flow $Q_f = Q_p$. The extra pressurized feed supply (Q_{extra}) originating from the DWEER device is not needed in CCD; however, at the same time the latter technology requires a somewhat larger conduits volume, suggesting that installation costs effectiveness of both technologies is about the same. Despite the similar projected installation costs of CCD and SWRO-DWEER, the former technology offers significant performance benefits (e.g. low energy without ER, low fouling and bio-fouling, high recovery, high flux, flexible operational conditions of modules and membranes etc.) of clear commercial value unmatched by the latter.

4.7. Present and future economic prospects of compared technologies

4.7.1. PFD

Future economic prospects of various conventional SWRO and BWRO technologies are measured in terms of costs of construction, energy, chemicals, maintenance, repairs, labour and finance in relation to revenues and profits on revenues over the investment return period. The growing worldwide reliance on desalination for water supply is manifested already by increased desalination capacity and reduced desalination costs with future forecast targets of short-terms (5 years) and long-terms (20 years) developments well defined. A recent comprehensive evaluation [5] of current status and future trends for ocean seawater (3.5%) desalination is noteworthy in particular since its provides the comparative data in brackets (minimum→maximum; 1st current; 2nd 5 years target; and 3rd 20 years target) of expected developments with regard to RO energy consumption (kWh/m^3: 2.00→3.00; 1.50→2.50; and 1.35→1.50); desalination recovery (%: 45→50; 50→55; and 55→65); membrane productivity (m^3/day/membrane: 24.1→46.3; 33.3→55.5; and 92.5→148.0); membrane useful lifetime (years: 5→7; 7→10; and 10→15); construction costs (US$/m^3/day: 1216→2162; 1081→1.747; and 541→946); and cost of water (US$/m^3: 0.54→0.81; 0.41→0.68; and 0.27→0.41). The significant progress in all aspects of PFD technologies over the past 60 years, including performance of membranes and effective ER means from pressurized brine, brought these technologies to the state-of-the-art level with very little room for improvements. Accordingly, it would appear difficult to see how the forecasted targets could be met merely on the basis of conventional PFD technologies which have reached maturity. The present status of ocean seawater desalination, as an example, represents the technical limitations of the existing knowledge which is unlikely to change much with improved components for the conventional PFD technology. Moreover, it is plausible that advance components used with conventional technology could perform much better if applied in the context of new methods of different operational principles not confined by the limitations of existing technologies. The cited forecast [5] of long-term targets clearly implies the evolution of new technologies as evidenced by the projected RO minimum energy 1.35 kWh/m^3 which is inconceivable by conventional SWRO if operated at a reasonable flux.

4.7.2. CCD

The methods and results cited above for CCD of seawater and brackish water over the past 2.5 years reveal exceptional innovations which enable reaching today all of the long-term (20 years) projected targets [5] of the desalination industry. The new CCD methods are characterized by low-energy consumption in the absence of ER, high recovery, reduced fouling, flexibly operation over a wide flux range without exceeding TC specifications and other undisputed experimentally confirmed features. For instance, Mediterranean water (4.1%) desalination by CCD was demonstrated over the flux range 8→40 lmh with up to 53% recovery. CCD RO energy at 13–14 lmh for Mediterranean water (4.1%) was found to be 2.00 kWh/m^3 under trial conditions [12] or 1.78 kWh/m^3 with improved efficiency of pumps (85% eff. of HP and 60% of CP) which manifest RO energy under 1.60 kWh/m^3 for ocean seawater (3.5%) desalination under the same conditions. Lower flux CCD operation is concomitant with lower RO energy and vice versa. Demonstrated 53% desalination recovery by CCD of Mediterranean water (4.1%) at practised flux of 13–15 lmh signifies the plausibility of 60–65% desalination recovery with ocean water (3.5%) under the same conditions. Moreover, flux in CCD is independent of system recovery; therefore, the rate of permeate production at a desired recovery level is a matter of choice which dictates the RO energy consumption. Long-term target [5] for SWRO membranes productivity range 46.3 m^3/day(8″)→148 m^3/day(16″) is already available today and could apply to CCD with reduced fouling and without exceeding TC specifications over wide ranges of desired flux and recovery. Low fouling characteristics desalination technology most obviously contributes to extended useful lifetime of membranes. The cited forecast [5] of short- and long-terms target for ocean seawater (3.5%) desalination also considers construction costs and cost of water. Components requirements comparison in the preceding section suggests similar construction costs for SWRO-DWEER and SWRO-CCD units of the same production capacity under same flux conditions. If the above referred SWRO-CCD units could be made to operate at higher flux by a small increment in construction cost, this would imply increased permeate production rate and yield lower specific cost (US$/m^3/day) of construction. Increased production rate of permeate coupled with higher desalination recovery made possible by

SWRO-CCD also accounts for extra savings in cost of pre-treatment installation; therefore, translate to even greater savings of construction costs. Low construction cost coupled with low energy cost and low maintenance cost due to reduced scaling and fouling implys that cited forecast [5] of short- and long-terms targets for cost of water is possible by the CCD technology already today.

4.7.3. Assessment

A recent status report [5] with forecast of short terms (5 years) and long terms (20 years) expected developments in desalination with emphasis on ocean seawater, when considered in the context of the already reported CCD results (cited above); leads to the conclusion that all future targets of the growing desalination industry could be met by the CCD Technology.

5. Concluding remarks

The newly conceived [10,15] and recently reported performance [11–13, [17,18] of the CCD technology reveal high recovery, low RO energy in the absence of ER, reduced scaling and fouling, wide range of operational flux without exceeding membranes TC specifications, and flexible online control of all principle desalination parameters, and imply superb performance characteristics unmatched by conventional PFD methods. The performance of the new CCD technology was demonstrated for sea water and brackish water applications with data from commercially operated units. Results of CCD applications reported [11–13, [17,18] thus far reveal performance which meets already today all stated [5] long-term (20 years) targets and objectives of the worldwide growing desalination industry. Further progress in CCD is currently being directed towards the development of general and specific commercial applications including processes for the treatment of difficult industrial effluent and for the decontamination of drinking water, these apart from the other traditional and non-traditional RO applications. The unique prospects of the high flux and high recovery CCD technology for special application are well illustrated [18] with the BWRO-CCD new method for nitrate removal from drinking water for a feed source of 200 ppm NO_3 to permeate level under 44 ppm average NO_3 at flux of 37 lmh with 90% recovery; thereby, suggesting the prospects for replacement of EDR by CCD for such application with high cost effectiveness. Last, it should be pointed out that the main bottleneck of many of the conventional PFD technologies is associated with scaling and fouling effects of tail and front elements, whereas, such problems are reduced or eliminated completely by CCD; thereby, providing a considerable added value not available by conventional technologies.

Acknowledgements

The author wishes to thank Mr Yohanan Or for his trust and initiative which led to the first CCD pilot and to Aquagro Fund L.P. for the financial support.

References

[1] M. Elimelech, Williams A. Philip, Science, 5 August 2011, vol. 333, 712–717 (and references therein).

[2] S. Loeb, S. Sourirajan, American chemical society advances in chemistry series, ACS 38 (1963) 117–132, and references therein.

[3] Hermoni, Actual energy consumption and water cost for the SWRO systems at palmachim—case history, IDA Conference, November 2–3, 2010, CA, USA.

[4] B. Liberman, Present and future: Energy efficiency seawater desalination, IDA Conference, November 2–3, 2010, CA, USA.

[5] N. Voutchkov, Membrane seawater desalination—overview and recent trends, IDA Conference, November 2–3, 2010, CA, USA (and reported data and citations).

[6] M.A. Sanz, R. L. Stover, Low energy consumption in the perth seawater desalination plant, IDA World Congress-Maspalomas, Gran Canaria, Spain, October 21–26, 2007 MP07.

[7] I. Bratt Russell, Method and apparatus for fluid treatment by reverse osmosis, US Patent No. 4,814,086.

[8] K. Jozzsef Szucs, A. Szucs, Method and apparatus for treating fluids containing foreign materials by membrane filter equipment, US Patent No. 4,983,301.

[9] A. Efraty, PCT International Publication No. WO O3/013704 A2, Variable pressure closed circuit desalination, February 20, 2003.

[10] A. Efraty, Apparatus for continuous closed circuit desalination under variable pressure with a single container, US Patent No. 7,628,921 (and related patents issued worldwide).

[11] 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. (in press).

[12] 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.

[13] 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. (in press).

[14] R.L. Stover, N. Efraty, Record low energy consumption with closed circuit desalination, IDA World Congress—Perth Convention and Exhibition Center (PCEC), Perth, Western Australia, September 4–9, 2011 (Ref: IDAWC/PER11-375).

[15] A. Efraty, Continuous closed circuit desalination apparatus without containers, US Patent No. 7,695,614 B2 (and related patents issued worldwide).

[16] A. Efraty, PCT International Publication No WO/2011/004364, entitled "Closed circuit desalination retrofit for improved performance of common reverse osmosis system", January 13, 2011.

[17] 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. (in press).

[18] 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. (in press).

[19] United States Environmental Protection Agency, Office of Water, 305(b) Report to Congress 1996/1998.

[20] World Health Organization, Guidelines for drinking-water quality, Health criteria and other supporting information, second ed., vol. 2, World Health Organization, 1996, pp. 940–949.

[21] A. Efraty, Z. Gal. Closed circuit desalination series No-7: Retrofit design for improved performance of conventional BWRO system, Desalin. Water Treat. (in press).