Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.793499

51 (2013) 7420–7430
December

Taylor & Francis
Taylor & Francis Group

Pressure retarded osmosis in closed circuit: a new technology for clean power generation without need of energy recovery

Avi Efraty

Osmotech Ltd., P.O. Box 132, Har Adar 90836, Israel
Tel. +972 52 4765 687; Fax: +972 2 5700262; email: efraty.adt@012.net.il

Received 23 June 2012; Accepted 6 March 2013

ABSTRACT

Power generation from salinity gradients by means of Pressure Retarded Osmosis (PRO) is currently preformed by conventional methods, wherein Energy Recovery (ER) is an essential feature without which such a process is impossible. The newly conceived Closed Circuit (CC) Pressure Retarded Osmosis technology (CC-PRO) described herein is based on a continuous consecutive sequential batch process; wherein, pressurized high salinity feed (HSF) is continuously supplied to the inlets of PRO modules and pressurized effluent removed from their outlets through internal circulation means by the alternating engagement/disengagement of two side conduits (SC). This process proceeds with high energy conservation without need of ER means. The new CC-PRO technology enables high operational flexibility achieved by set point selection of the permeation flux; the circulation flow; the applied pressure of power generation; and the flow ratio circulation/permeation which defines the salinity and osmotic pressure gradients inside the PRO modules. The high flexibility is manifested by the availability of an infinite number of set point combinations for the optimization of the process with respect to maximum power production under lower membrane detrimental effects and reduced fouling factors.

Keywords: Pressure retarded osmosis; Forward osmosis; Direct osmosis; Closed circuit desalination; Osmotic power; Osmotic gradient driven processes; Salinity gradient power; Clean energy sources

1. Introduction

The worldwide growing power demand due to rapidly expanding population and increased in standard of living, combined with the harmful "global green-house" effects created by excessive combustion of fossil fuels, have increased the awareness for the need of clean energy sources, such as hydro, wind, solar, geothermal, and biomass origin. A newly emerging source of gigantic clean energy production prospects is the so-called "osmotic power" derived from salinity gradients found worldwide where high and low salinity water sources are available next to each other [e.g. river water (~0.05%) next to sea water (SW: 3.5–4.5%); clear domestic effluents (~0.05%) next to SW (3.5–4.5%) or to brine (7–9%) from SW desalination; dead sea water (33%) next to Gulf of Eilate water (4.3%), etc.)]. For instance, a 3.5% salinity gradient created by a typical river–SW system manifests an osmotic pressure difference ($\Delta\pi$) of ~25 bar, equivalent to that of a 250 meter high hydroelectric dam, which may be used for continuous generation of low-cost clean electric energy of fixed power output and high availability essentially all day round, day and night irrespective of sun light and/or wind and/or weather conditions. Likewise, a 7.0% salinity gradient system of clean domestic effluent and brine from SW desalination plants creates an osmotic pressure difference ($\Delta\pi$) of ~50 bar available for clean power generation. The enormous power generation prospects through osmotic power prompted the rapidly growing interest in this noteworthy area of clean energy.

Osmosis is a natural process of enormous physiological importance for the transport of fluids across selective membranes as a result of concentration gradients. The application of Reverse Osmosis (RO) for salt water desalination was demonstrated first by Loeb and Sourirajan [1] in the early 60s of last century and since this approach became the method of choice for desalination worldwide. In the mid 70s of last century, Loeb [2,3] demonstrated the application of Forward Osmosis (FO) for power generation by utilizing osmotic pressure gradient across semi-permeable membranes and introduced the term Pressure Retarded Osmosis (PRO) for such a process. In spite the enormous prospects of PRO for clean energy generation in gigantic amounts from natural salinity gradients, progress [4] made in this area since inception has been relatively slow due to an inadequate conceptual approach and lack of suitable membranes of sufficient performance characteristics. The original conceptual approach to PRO with apparatus of Fig. 1 type design has been demonstrated by the *Statkarft* program [5–7] in Norway and the "*Mega-ton Water System Project*" [8–10] in Japan. The original approach is based on supply of nonpressurized Low Salinity Feed (LSF) combined with pressurized High Salinity Feed (HSF) on different sides of semi-permeable membrane surfaces at inlet to a PRO module; wherein, FO permeation takes place by PRO under declined Net Driving Pressure (NDP) with transformation of HSF to High Salinity Diluted Feed (HSDF) and of LSF to Low Salinity Concentrate (LSC) at the respective PRO module outlets. The flow pattern in the high pressure section of the design under review in Fig. 1 (hereinafter "conventional" design) consists of HSF flow (Q_{HSF}) at inlet to module which combines with the permeation flow (Q_p) produced by FO to afford module outlet flow ($Q_{HSF} + Q_p$) of HSDF which splits into two streams with Q_p applies for power generation by means of a turbine (T) driven electric generator (G) and Q_{HSF} for Energy Recovery (ER) by means of the ER device PX-ER; whereby, pressurized HSF (Q_{HSF}) is supplied to the system. Power (kW) generation in this system proceeds according to Eq. (1); wherein, Q_p (m^3/h) stands for permeation flow, Δp (bar) for the applied pressure for power generation and f_{TG} for the overall efficiency of the turbine-generator (TG) system. The other features in Fig. 1 include the low-pressure HFS booster pump (HSP-BP) and the LSF supply pump (LSF-P).

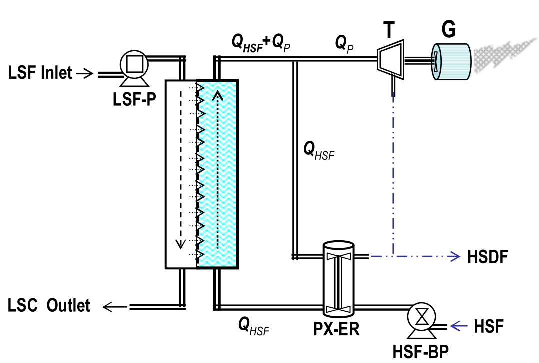

Fig. 1. Illustration of a single module conventional PRO power generation system.

According to an ideal theoretical model by Lee et al. [11], water permeation flux (J) in PRO is expressed by Eq. (2); wherein, A stands for the membrane permeability coefficient, $\Delta\pi$ for the osmotic pressure difference ($\pi_{HSF} - \pi_{LSF}$) and Δp for the applied hydraulic pressure difference ($p_{HSF} - p_{HSF}$). Power density (W) according to this model is expressed by Eq. (3) and its differentiation with respect to Δp yields the maximum power density (W_{max}) term expressed by Eq. (4) under the specified pressure conditions expressed by Eq. (5).

In practice, the ideal PRO model requires modifications in order to account for internal and external concentration polarization effects of semi-permeable membranes that are related to their compositions and structures. The so-called detrimental effects cause the lowering of the ideal osmotic pressures and thereby effect both $\Delta\pi$ and the net-driving pressure ($\Delta\pi - \Delta p$) with effective flux (J_{eff}) under such conditions expressed by Eq. (6); wherein, β stands for actual/ideal flux ratio of a specific membrane element which enables to translate theory into practice. In this context noteworthy are the extensive theoretical and experimental studies of recent [4,12–16] years in order to assess the impact of detrimental effects on the performance of various types of semi-permeable membranes with the intend to develop suitable effective membranes for PRO and FO, processes which are expected to play an important role in future water technologies.

(1) $P = (1/36) \times Q_p \times \Delta p \times (1/f_{TG})$
(2) $J = A \times (\Delta\pi - \Delta p)$
(3) $W = J \times \Delta p = A \times (\Delta\pi - \Delta p) \times \Delta p$

(4) $W_{max} = (1/4) \times A \times (\Delta\pi)^2$
(5) $\Delta p = \Delta\pi/2$
(6) $J_{eff} = \beta \times A \times (\Delta\pi - \Delta p)$

The ER device (PX-ER) is the key feature of the conventional PRO technology for power generation exemplified in Fig. 1 without which the entire concept becomes invalid even with a satisfactory membrane performance. The crucial reliance of conventional PRO on ER implies added mechanical, hydraulic, and process control complexity which translates to installation costs, running expenses, and lower than expected power production availability after accounting for the losses of the ER device and the auxiliary pumps in the system. Avoiding the crucial reliance of the conventional PRO on ER required the development of a different conceptual approach which circumvents the need for ER and such a new approach is described next.

2. Batch PRO in Closed Circuit (CC-PRO) without ER

The concept of low energy and high recovery Closed Circuit Desalination (CCD) without need for ER from brine was recently demonstrated for SW [17,18,22] and Brackish Water [19–21,23]. A similar concept of Closed Circuit (CC) PRO without need of ER described hereinafter opened the door to perform such processes with greater flexibility, higher internally created power efficiency, and lower installation costs.

The new PRO approach is exemplified with the single module design displayed in Fig. 2A for a batch CC-PRO process; wherein, the applied pressure (Δp) is a part of the internally created $\Delta\pi$, and whereby, the HSF at module inlet is supplied through a side conduit (SC) which also serves to collect the HSDF effluent. Cross flow (Q_{CP}) in the design under review originates from a circulation pump (CP) equipped with *vdf* and controlled at a selected fixed flow rate by Flow Meter (FM_{CP}) means. Fixed permeation flow rate (Q_p) in Fig. 2A is achieved through a Variable Flow Valve (VFV) means controlled by a Flow Meter (FM_t) and/or by turbine's shaft revolution meter means(not displayed). A selected permeation flow (Q_p) also defines the flow rate difference $Q_{lsc} - Q_{lsc}$ of inlet to outlet in the low pressure section of the module. The power output (kW) of the CC-PRO design under review (Fig. 2A) is expressed by $(1/36) \times Q_p \times \Delta p \times (1/f_{TC})$; wherein, flow is expressed in m^3/h, pressure in bar, and f_{TC} stands for the efficiency factor of the TG system. The HSF at module's inlet in the batch CC-PRO design under review (Fig. 2A) experiences the same applied pressure selected for the entire system without need for ER, since the entire energy of the system is conserved and this in the absence pressurized HSDF release to the outside of the CC.

The duration of the batch operation in the design under review (Fig. 2A) is confined by the volume of the SC and after all the HSF in the SC is replaced by HSDF, the process needs to be stopped for the recharge of the SC with fresh feed. The configuration of the apparatus during the recharge process of the SC is displayed in Fig. 2B and proceeds at near atmospheric pressure with CP stopped, VFV closed, and valve means in the SC appropriately positioned to enable the HSDF replacement by HSF with HSF-P. After recharge completed, HSF-P is stopped, SC sealed by the appropriately positioned valve means and then the VFV-TG system activated to enable the initiation of a new CC-PRO sequence of power generation.

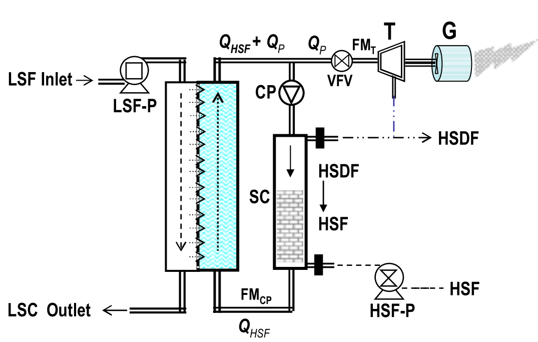

Fig. 2A. A single module batch CC-PRO apparatus in operation performing power generation in CC through a SC without need of energy recovery.

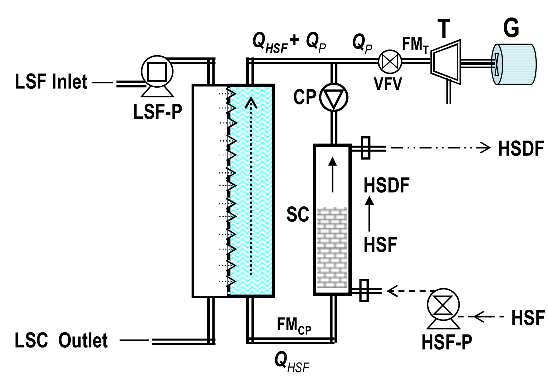

Fig. 2B. A single module batch CC-PRO apparatus with power generation stopped to enable HSDF replacement by fresh HSF at near atmospheric pressure by means of the HSF-P pump.

3. Continuous PRO in Closed Circuit (CC-PRO) without ER

The CC-PRO batch process depicted in Fig. 2A and B can be made continuous for an uninterrupted power generation by means of a consecutive sequential process with an apparatus of the design displayed in Fig. 3 with two alternating SCs, one of which is always engaged with the CC for pressurized HSF supply to the inlet of the module and pressurized HSDF withdrawal from its outlet without need of ER. The design displayed in the figure under review shows two SCs, labeled SC1 and SC2, with their valve means to enable engagement/disengagement with the CC as well as for recharge with fresh HSF feed. The sequential stage of operation displayed in the figure is that of an engaged SC1 with the pressurized CC, while the disengaged decompressed SC2 undergoing HSDF replacement by HSF after which it will be sealed, compressed by connecting to the CC through just one of its valve means, and left on stand-by for the next engagement. The decompression and compression of the disengaged SCs during the recharge operation proceeds with the loss of negligible amounts of hydrostatic energy and this feature was already confirmed [17,18,22] experimentally during the related process of CCD of SW which proceeds with high recovery and exceptionally low energy without need of ER.

The illustration of the new CC-PRO technique with a single module apparatus is done for clarity, simplicity, and convenience of presentation, whereas in practice, such apparatus may comprise any desired number of PRO modules with their respective inlets and outlets connected in parallel to the principle CC with its alternating SCs, as is exemplified in Fig. 4 for a design with five PRO modules. The somewhat expanded design displayed in Fig. 4 illustrates the modularity features of the new CC-PRO technology with emphasis of the parallel linkage of the joint modules. Another noteworthy aspect in Fig. 4 relates to the size of SCs in an expanded CC-PRO design which need not be large. The volume (V) of a SC in an expanded CC-PRO design should account for the recharge time of the disengaged SC by HSF-P, the valve means actuation time during the steps of SC disengagement/engagement, and the brief stand-by time before the recharged compressed SC is engaged again. The selection of fast flow HSF-P, valves means of fast actuation modes, and a brief stand-by period before engagement would dictate a rather small SC volume relative to the intrinsic volume of the PRO modules in the CC. The control of such a process by the alternating engagement/disengagement of SCs is already well established for CCD [17–23] and should apply without apparent difficulty to CC-PRO as well.

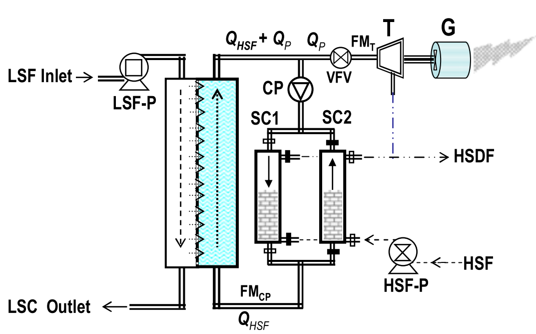

Fig. 3. A single module CC-PRO apparatus for continuous power generation by a consecutive sequential batch process with two alternating SCs without need for energy recovery.

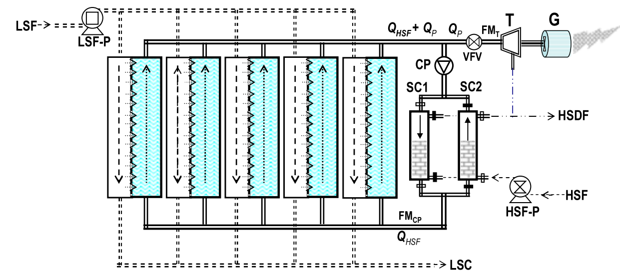

Fig. 4. A five modules CC-PRO apparatus for continuous power generation by a consecutive sequential batch process with two alternating SCs without need for ER.

4. Simulations of power generation by CC-PRO

Power generation by PRO greatly depends on the performance characteristics of selected membrane in the context of the selected technology, and in this regards the simulated data presented hereinafter relates to the CC-PRO design in Fig. 3 of a single PRO module with presumed net intrinsic volume of 49 l, membrane surface area of 28 m^2, permeability coefficients (A) of 7.70 l/m^2/h/bar and diffusion coefficient (B) of 6.67 l/m^2/h. The selected membrane characteristics, especially with regards to A and B coefficients, resemble the recently reported [13] data for a modified TFC-RO SW30-HR commercial membrane. The use of such a modified commercial membrane for the suggested CC-PRO application is conditioned by its sufficient mechanical stability to withstand the applied pressures revealed during the specific simulations described hereinafter. Data base of a typical power generation simulation by the CC-PRO design with a membrane of the cited specifications is illustrated in

Table 1
Power generation simulation of a single module CC-PRO unit with ocean (3.5%)–river (0.05%) gradient system using $Q_{CP}/Q_p = 1.0$ and a membrane of $A = 7.70\,\mathrm{l/m^2/h/bar}$

3.50	% HSF	26.3 bar OP
0.050	% LSF	0.35 bar OP
		25.9 bar Δπ

Design & Membrane Data

1	Number of Modules
1	No of Membrans per Module
260	cm length of Module
20	cm diameter of Module
81.6	liter gross volume of Module
40.0	% membrane volume in Module
49.0	liter net volume of Module
49.0	liter net volume of entire design
28.0	m2 membrane surface area
28	m2 total surface area of design

LSF-LSC Performance Data

Module	Unit	
3.78	3.78	m3/h Inlet Flow
0.05	0.05	% Inlet Salinity
0.76	0.76	m3/h Outlet Flow
0.25	0.25	% Outlet Salinity
0.76	0.76	m3/h Permeation Flow
0.15	0.15	% mean Salinity (inlet+outlet)/2
1.13	1.13	bar mean Δπ=[(inlet+outlet)/2]
0.20	0.20	Ratio Qlsc/Qlsf Qp=Qlsf-Qlsc

PRO Membranes Detrimental Effect

0.38	Ratio Actual/Ideal assumed

Fixed Flux per Single Module

27.0	lmh Flux (actual Module average)
0.76	m3/h (Q_p) Module average Permeate
12.60	lpm Module average Permeate

Recycling Flow of Single Module

0.76	m3/h recycling flow (CP)
12.6	lpm recycling flow of module (CP)
3.89	minute complete volume recycle
1.00	Selected Flow Ratio (Q_{CP}/Q_p)

Flow of Entire Design

0.76	m3/h Permeate Flow of entire unit
0.76	m3/h Recycling Flow of entire unit

HSF - HSDF Module Inlet & Outlet Data

3.50	% HSF Module Inlet
25.9	**bar Δπ Module Inlet**
1.78	% HSDF Module Outlet
11.4	**bar Δπ Module Outlet**
2.64	% HSDF average
18.7	**bar Δπ Module average**
7.50	**bar/% - conversion factor**

Power Demand by PRO PUMPS

Performance	HSF	LSF	CP
m3/h	0.76	3.78	0.76
bar	**0.25**	**0.25**	**0.25**
Efficiency assumed	**0.75**	**0.75**	**0.75**
Watt	**7.0**	**35.0**	**7.0**

TOTAL Pumps Demand Power (W)	49.0
TOTAL Pumps Demand PD (W/m2)	1.75
Actual PRO only (W/m2)	**7.00**
Actual PRO less Pumps (W/m2)	**5.25**
Turbine-Generator % Efficiency	**90**
Actual Electric Power (w/m2)	**4.72**

ACTUAL PRESSURES and FLUX

Permeability Coefficient			**7.70**
Module	Pressure bar	NDP bar	Flux lmh
Applied	9.3		
Δπ MOD Inlet	25.9	16.5	48.4
Δπ MOD Outlet	11.4	2.1	6.2
Δπ MOD average	18.7	9.3	27.3
PRO Actual average Flux used			27.0

Table 1 for a salinity gradient system comprising Ocean water (3.5%–35,000 ppm) and river water (0.05%–500 ppm) under an average flux of 27 lmh; flow rates ratio of $Q_{CP}/Q_p = 1.0$ in the pressurized section and $Q_{lsc}/Q_{lsf} = 0.2$ in the nonpressurized section of the module; membrane detrimental effects of assumed Actual/Ideal = 0.38 flux ratio; and with assumed 75% efficiency for the HSF, LSF, and CP pumps and 90% efficiency for the TG system. The simulation under review pertains to stationary steady-state equilibrium conditions inside the CC-PRO module with respect to salinity and osmotic pressure gradients, with half the average osmotic pressure gradient selected as an applied pressure for power generation. The module average ideal NDP is the difference between the average ideal osmotic pressure and the applied pressure, with effective flux (J_{eff}) derived from Eq. (6); wherein, detrimental effects are accounted by the Actual/Ideal flux ratio $\beta = 0.38$ (62% of the ideal flux is lost due to membrane's detrimental effects). The value of correction factor β is estimated on the basis of the reported [13] detrimental effects characterized for the modified TFC-RO SW30-HR membrane. The salinity and osmotic pressure gradients created inside the CC-PRO module under the specified equilibrium state conditions depend only on the flow ratio Q_{CP}/Q_p and remain essentially unchanged as long as this ratio is fixed. The values in Table 1 entitled "ACTUAL PRESSURE and FLUX" pertain to the stationary state Δπ, NDP, and J_{eff} at module's inlet and outlet as well as to their average. The average operational flux (27.0 lmh) under the specified flow ratio (1.0) in Table 1 is selected to be just below (0.3 lmh) the available average flux (27.3 lmh) in order to maximize the power output of the system.

The time scale CC-PRO simulation results under the conditions specified in Table 1 of module salinity gradient, osmotic pressure, power output, and power density are displayed in Fig. 5. The power output of the CC-PRO unit under the conditions specified in Table 1 was also ascertained in the flow ratio (Q_{CP}/Q_p) range 1–3, with average operational flux selection of 0.3 lmh under the available flux per each flow ratio, and the results of the this analysis are displayed in Fig. 6. The simulation under review reveals an uninterrupted continuous CC-PRO operation by means of alternating SCs according to the design displayed in Fig. 3. It should be pointed out that the simulated performance under review is fully consistent with the

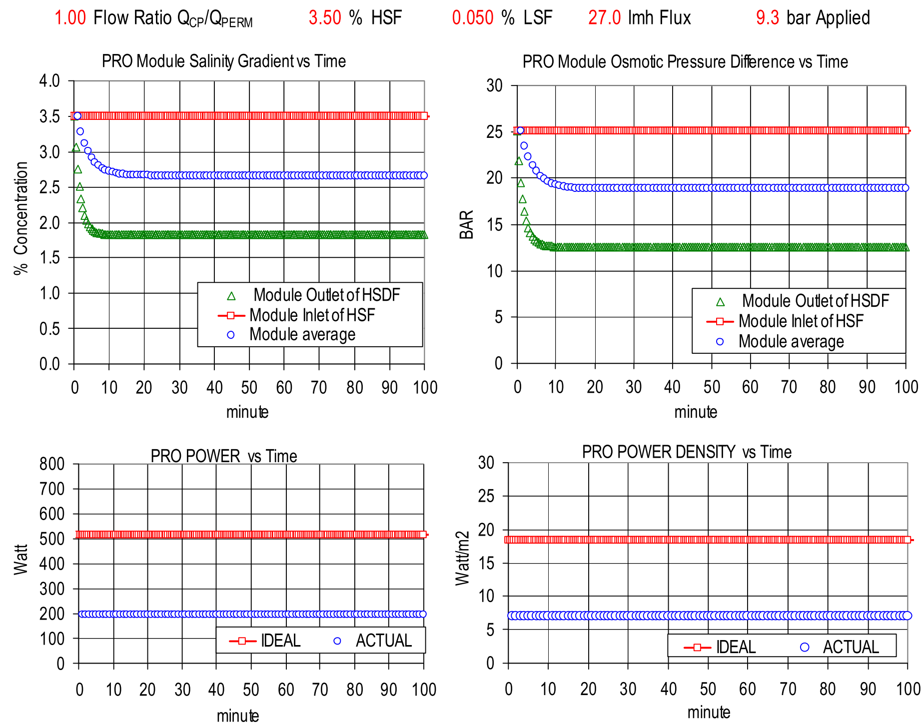

Fig. 5. CC-PRO performance characteristics of a single module CC-PRO unit with the salinity gradient system 0.05–3.5% under the conditions specified in Table 1.

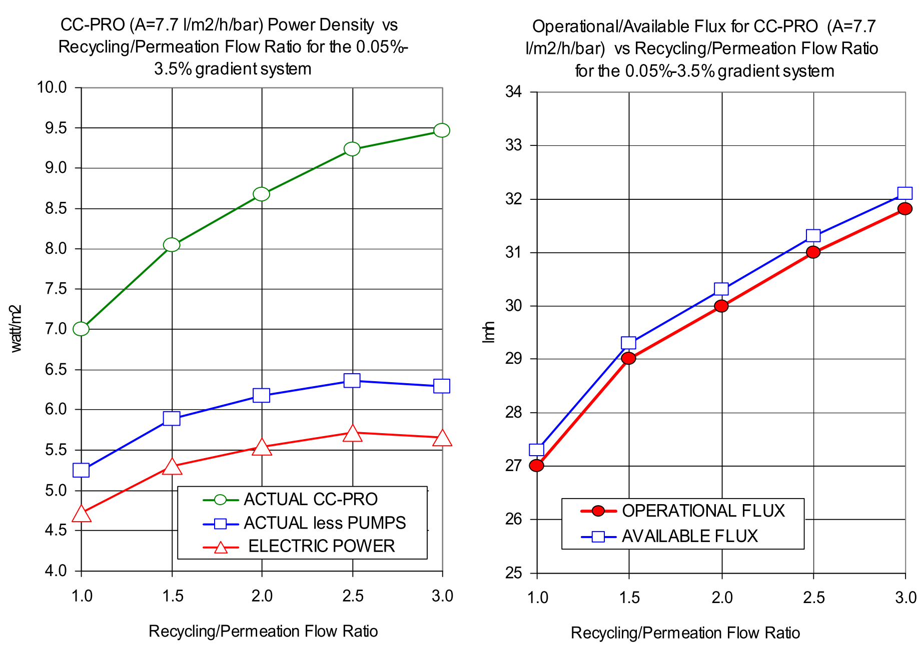

Fig. 6. Power output of the CC-PRO unit with the salinity gradient system 0.05–3.5% under the conditions specified in Table 1 except for recycling/permeation flow ratio changes in the range 1.0–3.0 with actual flux selection of 0.3 lmh below the available flux.

existing PRO theory, except with regards to applied pressure which in case of the conventional technique originates from an ER device, whereas in case of CC-PRO such a device is circumvented.

Table 2
Power generation simulation of a single module CC-PRO unit with a salinity gradient system of brine (7.0%) from ocean water desalination with 50% recovery and clean domestic effluents (0.05%) using $Q_{CP}/Q_p = 1.0$ and a membrane of $A = 7.701/m^2/h/bar$

7.00	% HSF	52.5	bar OP
0.050	% LSF	0.35	bar OP
		52.2	bar Δπ

Design & Membrane Data

1	Number of Modules
1	No of Membrans per Module
260	cm length of Module
20	cm diameter of Module
81.6	liter gross volume of Module
40.0	% membrane volume in Module
49.0	liter net volume of Module
49.0	liter net volume of entire design
28.0	m2 membrane surface area
28	m2 total surface area of design

LSF-LSC Performance Data

Module	Unit	
7.81	7.81	m3/h Inlet Flow
0.05	0.05	% Inlet Salinity
1.56	1.56	m3/h Outlet Flow
0.25	0.25	% Outlet Salinity
1.56	1.56	m3/h Permeation Flow
0.15	0.15	% mean Salinity (inlet+outlet)/2
1.13	1.13	bar mean Δπ=[(inlet+outlet)/2]
0.20	0.20	Ratio Qlsc/Qlsf Qp=Qlsf-Qlsc

PRO Membranes Detrimental Effect

0.38	Ratio Actual/Ideal assumed

Fixed Flux per Single Module

55.8	lmh Flux (actual Module average)
1.56	m3/h (Q_p) Module average Permeate
26.04	lpm Module average Permeate

Recycling Flow of Single Module

1.56	m3/h recycling flow (CP)
26.0	lpm recycling flow of module (CP)
1.88	minute complete volume recycle
1.00	Selected Flow Ratio (Q_{CP}/Q_p)

Flow of Entire Design

1.56	m3/h Permeate Flow of entire unit
1.56	m3/h Recycling Flow of entire unit

HSF - HSDF Module Inlet & Outlet Data

7.00	% HSF Module Inlet
52.1	**bar Δπ Module Inlet**
3.53	% HSDF Module Outlet
24.6	**bar Δπ Module Outlet**
5.26	% HSDF average
38.3	**bar Δπ Module average**
7.50	**bar/% - conversion factor**

Power Demand by PRO PUMPS			
Performance	HSF	LSF	CP
m3/h	1.56	7.81	1.56
bar	0.25	0.25	0.25
Efficiency assumed	0.75	0.75	0.75
Watt	14.5	72.3	14.5
TOTAL Pumps Demand Power (W)			101.3
TOTAL Pumps Demand PD (W/m2)			3.62

Actual PRO only (W/m2)	**29.72**
Actual PRO less Pumps (W/m2)	**26.10**
Turbine-Generator % Efficiency	90
Actual Electric Power (w/m2)	**23.49**

ACTUAL PRESSURES and FLUX

Permeability Coefficient			7.70
Module	Pressure bar	NDP bar	Flux lmh
Applied	19.2		
Δπ MOD Inlet	52.1	33.0	96.4
Δπ MOD Outlet	24.6	5.4	15.8
Δπ MOD average	38.3	19.2	56.1
PRO Actual average Flux used			55.8

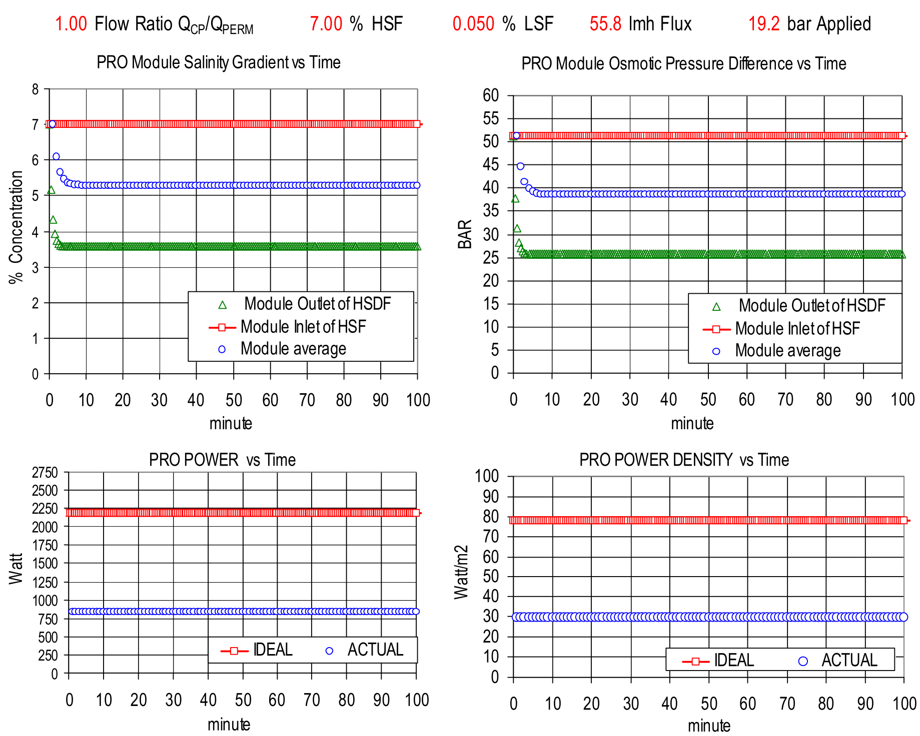

Fig. 7. CC-PRO performance characteristics of a single module CC-PRO unit with the salinity gradient system 0.05–7.0% under the conditions specified in Table 2.

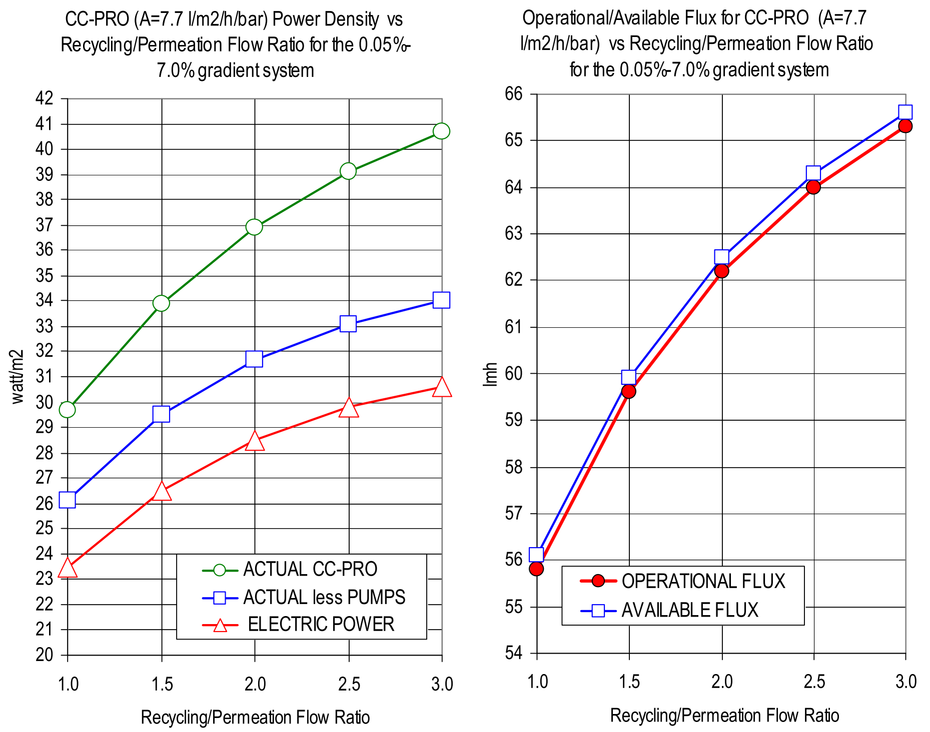

Fig. 8. Power output of the CC-PRO unit with the salinity gradient system 0.05–7.0% under the conditions specified in Table 2 except for recycling/permeation flow ratio changes in the range 1.0–3.0 with actual flux selection of 0.3 lmh below the available flux.

In light of the worldwide increased capacity of sea water desalination plants, PRO power generation using brine (e.g. 7.0%) from Ocean water desalination with 50% recovery and treated sewage water (e.g. 0.05%) is a noteworthy prospective source of clean energy especially where domestic effluents are not being used for irrigation [8–10,24,25]. This application in the context of CC-PRO is illustrated in Table 2 and Figs. 7 and 8, by complete analogy with the respective data in Table 1 and Figs. 5 and 6, assuming that the selected membrane withstands the applied pressure of ~20 bar which is required in this process. The use of this salinity gradient for power generation is of special interest, since over 60% of the global population concentrates along sea water shores where demand for SWRO desalination is high and treated domestic effluents disposed rather than reused. The hybrid SWRO–PRO approach could furnish part of the energy required for desalination by the reuse of brine and waste domestic effluents; thereby, fulfill several noteworthy environmental objectives simultaneously.

5. Discussion

The new CC-PRO technology differs conceptually from the conventional PRO approach in several aspects, although both obey the same principle FO equations pertaining to the permeation flux (J) as function of NDP ($\Delta\pi - \Delta p$) according to Eq. (2); permeation power density according to Eq. (3); permeation flow according to $J \times S$; wherein S stand for membrane surface area and permeation power according to Eq. (1). In contrast with the essential ER requirement of conventional PRO, the new approach (CC-PRO) proceeds with near absolute energy retention in the CC without need of ER, since the steps of compression/decompression associated with the alternating SCs take place under hydrostatic conditions with negligible loss of energy. The ability of a single SC engagement to effect near absolute energy conversion efficiency was recently reported in the context of CCD of sea water [17,18,22] and of Brackish Water [18–21,23] which revealed near absolute RO energy consumption without need of ER. Accordingly, the effective implementation of the alternating SCs technique with PRO is bound to lead to a similar result of high energy conversion efficiency directed towards greater hydroelectric power generation without need of ER. The applied pressure (Δp) in conventional PRO is essentially the external pressure provided by the ER device, an expensive pump driven hydraulically by the disposed pressurized HSDF flow. ER efficiency in conventional PRO is rather an important issue because the net power generation availability greatly depends upon the ability to conserve the energy stored in the disposed pressurized HSDF flow and this dictates the need for an highly efficiency ER device. The energy conversion effectiveness of ER devices (e.g. PX) in existing PRO apparatus is not entirely clear in the absence of reported information, however, some relevant information in this context is available from reported operational data of advanced SW desalination plants. Experience gained in the operation of well designed modern large SWRO plants worldwide with advanced ER means (e.g. PX and DWEER) reveals [22] an energy conversion efficiency range of 70–80%, well below the claimed (90–95%) ER efficiency of advanced ER devices, and this may suggest adverse integration effects when many ER devices are operated simultaneously in the same desalination plant. The choice ER for conventional PRO is an issue of considerable significance from the stand points of power generation efficiency and installation costs; whereas, such an issue doesn't exist with CC-PRO since energy conversion is near absolute in the absence of ER.

In contrast with conventional PRO, applied pressure in CC-PRO is a selected fraction of the internally generated osmotic pressure used for power generation under desired flux conditions. The flux distribution in a conventional PRO module relates to NDP at inlet (maximum: $\Delta\pi - \Delta p$) and outlet (minimum: $\Delta\pi - \Delta p \approx 0$ since $\Delta\pi \approx \Delta p$) with average NDP [=(inlet + outlet)/2] under maximum power density conditions ($\Delta p = \Delta\pi/2$) expressed by $\Delta\pi/4$; wherein, $\Delta\pi$ stands for the osmotic pressure difference of the original salinity gradient constituents. Incidentally, the $\Delta\pi/4$ applied pressure for maximum power density is manifested by the term $(1/4)\Delta\pi^2$ [or $(\Delta\pi/2)^2$] in Eq. (4). In accordance with the aforementioned, the selected applied pressure in the simulations displayed in Tables 1 and 2 was $\Delta\pi/2$; wherein, $\Delta\pi$ stands for the average between module's inlet and outlet osmotic pressures difference at the point of maximum power density according to the CC-PRO simulations. The information presented in these tables also pertains to $\Delta\pi$ at module's inlet, outlet, and their average as well as to the respective NDP and actual flux terms. The terms maximum, minimum, and average flux cited in the tables are the actual values which take into account of the membrane permeability coefficient (7.71/m2/h/bar) and the Actual/Ideal flux ratio correction factor (0.38) for the membrane detrimental effects. The parameters in the "ACTUAL PRESSURES and FLUX" section of the tables remain unchanged per fixed Q_p/Q_{CP} operational flow ratio, and the actual average flux of operation selected under such conditions is just below (~0.3 lmh) the maximum average available flux.

The principle parameters in the simulated Data Base Form, exemplified in Tables 1 and 2, are entered in compliance with the specific salinity gradient system, the membrane characteristics, and the elected internal osmotic pressure fraction intended as the applied pressure for power generation. The selected applied pressure of $\Delta\pi/4$ in Tables 1 and 2 is not mandatory and any other desired osmotic pressure fraction may be used for such a purpose. The selection of an average operational flux just under the maximum available average flux revealed in Tables 1 and 2 and manifested in Figs. 4–7 is not mandatory; any other desired average operational flux may be selected provided that the maximum available flux is not exceeded.

Apart from avoiding the need for ER, the CC-PRO technology offers enormous operational flexibility with infinite combinations of set points selections, including such of permeation flow (Q_p), cross flow (Q_{CP}) and their ratio (Q_{CP}/Q_p) which dictate the entire behavior of the PRO module with respect to salinity and osmotic pressure gradients and define its power density and power generation prospects. The aforementioned is exemplified for two different salinity gradient systems in Tables 1 and 2 with pertinent simulated results of module salinity, osmotic pressure, power density, and power output revealed in Figs. 4 and 6, respectively, under the fixed flow ratio $Q_{CP}/Q_p = 1.0$ conditions. Flux and power density variations as a function of flow ratio (Q_{CP}/Q_p) selection in the range 1–3 in said salinity gradients systems reveal (Figs. 5 and 7) increased available flux and power density concomitant with increased flow ratio, thereby, a simple procedure to enable performance optimization. The wide range control prospects of permeation flow and cross flow, independent of each other, by CC-PRO is noteworthy, since should allow for process optimization also with respect to membrane detrimental effects; and thereby, improve the power generation capability such systems.

Specifically, developed membranes for FO and PRO applications are not yet commercially offered and much of the information regarding such advanced membranes is presently confidential. Accordingly, the selected membrane for CC-PRO simulations reported hereinabove was assumed to posses a sufficient mechanical stability to withstand the applied pressures cited in the simulations. The permeability coefficient of the selected membrane was presumed to be same as that recently reported [13] for a certain modified TFC-RO SW30-HR element which may be used for CC-PRO applications pending its sufficient mechanical stability. The selection of membranes for FO and PRO applications will be greatly simplified when such membranes become commercially available in the near future.

The CC-PRO simulation results described in Table 1 and Figs. 5 and 6 are of special interest in the context of the salinity gradient system of sea water and river water for clean power generation pioneered [5–7] by *statkraft* in Norway, or similar salinity gradient systems where river water replaced by treated domestic effluents. The harvesting of cheap clean energy in large amounts worldwide around sea water shores where over 60% of the global population is concentrated provides a real incentive of considerable prospects for PRO techniques at large and for CC-PRO in particular in light of its simplicity, flexibility, and cost effectiveness.

The CC-PRO simulation results described in Table 2 and Figs. 7 and 8 are of special interest in the context of the salinity gradient system of brine from sea water desalination plants and treated domestic effluents, or other low salinity effluents. This noteworthy approach of integrated sea water desalination plants with sewage treatment centers, pioneered by the Japanese "*Mega-ton Water System Project*" [8–10], provides an ideal local solution for the reuse of such effluents for cheap and clean power generation which may be diverted back to the desalination plants and reduce their energy costs. The present status of this program is already manifested by the reported [8–10] power density output of $7.7\,W/m^2$ with expectation to reach $12\,W/m^2$ within two years and $16\,W/m^2$ in the near future.

6. Outlook

Compared with conventional PRO, the newly conceived CC-PRO technology offers a conceptually different approach of some noteworthy operational features as followed:

(1) *ER*: CC-PRO power generation in the absence of ER device with essentially absolute conservation of the energy stored in the disposed pressurize HSDF effluent, except for negligible hydrostatic energy losses encounter during the compression/decompression steps of the SCs.
(2) *Permeation flow*: Flexible permeation flow (Q_p) selection irrespective of cross flow.
(3) *Cross flow*: Flexible cross flow (Q_{CP}) selection irrespective of permeation flow.
(4) Q_{CP}/Q_p *Flow ratio*: Flexible flow ratio selection over a wide range with each ratio manifesting a different PRO steady state conditions and power generation prospects.
(5) *Permeation flux*: Flexible permeation flux selection within the maximum available for a given Q_{CP}/Q_p flow ratio.
(6) *Applied pressure for power generation*: Flexible applied pressure selection within the maximum available flux per each fixed flow ratio.
(7) *A simple technology of high cost effectiveness:* A method of simple modular designs on the basis of a consecutive sequential hydrostatic process without need of ER for any desired number of PRO modules which utilizes common, inexpensive parts and components of high cost effectiveness.

The above listed features point out to an exceptional performance flexibility with infinite combinations of operational set points for the optimization the PRO process such that maximum power output could be attained under conditions of reduced concentration polarization detrimental effects and low fouling characteristics with high cost effectiveness, unmatched by any existing PRO technique.

References

[1] S. Loeb, S. Sourirajan, American chemical society advances in chemistry series, ACS 38 (1963) 117–132 (and references therein).
[2] S. Loeb, Method and apparatus for generating power utilizing pressure-retarded-osmosis, US patent No 3,906,250, 1975.
[3] S. Loeb, Osmotic-power plants, Science 189 (4203) (1975) 654–655.
[4] A. Achilli, A. E. Childress, Pressure retarded osmosis: From the vision of Sindney Loeb to the first prototype installation—Review, Desalination 261 (2010) 205–211 (and references therein).
[5] S.E. Skilhagen, J.E. Dugstad, R.J. Aaberg, Osmostic power—-power production based on the osmotic pressure difference between waters and varying salt gradients, Desalination 220 (2008) 476–482.
[6] S.E. Skilhagen, G. Brekke, W.K. Nielsen, Progress in the development of osmotic power, in: 2011 Qingdao International Conference on Desalination and Water Reuse, Proceedings, June 20–23, Qingdao, China, 2011, pp. 247–260.
[7] G. Brekke, Review of experience with the Statkraft prototype plant, in: The Third Osmosis Membrane Summit, April 26–27, Barcelona, Spain, 2012.
[8] A. Tanioka, Power generation by pressure retarded osmosis using concentrated brine from sea water desalination system and treated sewage, review of experience with pilot in Japan, in: The Third Osmosis Membrane Summit, April 26–27, Barcelona, Spain, 2012.
[9] M. Kurihara, Government funded programs worldwide, the Japanese "Mega-ton Water System" project, in: The Third Osmosis Membrane Summit, April 26–27, Barcelona, Spain, 2012.
[10] K. Saito, M. Irie, S. Zaitsu, H. Sakai, H. Hayashi, A. Tanioka, Retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water, Desalin. Water Treat. 41(3) (2012) 114–121.

[11] K.L. Lee, R.W. Baker, H.K. Lonsdale, Membrane for power generation by pressure retarded osmosis, J. Membr. Sci. 8 (1081) 141–171.
[12] N.Y. Yip, M. Elimelech, Thermodynamic and energy efficiency analysis of power generation from natural salinity gradients by pressure retarded osmosis, Environ. Sci. Technol. 46 (2012) 5230–5239.
[13] N.Y. Yip, M. Elimelech, Performance limiting effects in power generation from salinity gradients by pressure retarded osmosis, Environ. Sci. Technol. 45 (2011) 10273–10282.
[14] N.Y. Yip, A. Tiraferri, W.A. Phillip, J.D. Schiffman, L.A. Hoover, Y.C. Kim, M. Elimelech, Thin-film composite pressure retarded osmosis membranes for sustainable power generation from salinity gradients, Environ. Sci. Technol. 45 (2011) 4360–4369.
[15] N.Y. Yip, A. Tiraferri, W.A. Phillip, J.D. Schiffman, M. Elimelech, Performance thin-film composite forward osmosis membrane, Environ. Sci. Technol. 44 (2010) 3812–3818.
[16] J.R. McCutcheon, M. Elimelech, Influence of membrane support layer hydrophobicity on water flux in osmoticaly driven membrane process, J. Membr. Sci. 318 (2008) 458–466.
[17] A. Efraty, R.N. Barak, Z. Gal, Closed circuit desalination – a new low energy high recovery technology without energy recovery, Desalin. Water Treat. 31 (2011) 95–101.
[18] A. Efraty, R.N. 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.
[19] 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.
[20] 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.
[21] 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.
[22] 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.
[23] 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.
[24] S. Chou, R. Wang. L. Shi, C.Y. Tang, A.G. Fane, Thin film composite hollow fiber membranes for pressure retarded osmosis (PRO) process with high power density, J. Membr. Sci. 389 (2012) 25–33.
[25] W. Rong, C. Tang, T. Fane, Development of pressure retarded osmosis (PRO) membranes with high power density for osmotic power harvesting, in: The Third Osmosis Membrane Summit, April 26–27, Barcelona, Spain, 2012.