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Analysis of specific energy consumption in reverse osmosis desalination processes

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ABSTRACT

This paper aims to quantify the contribution of the various factors to energy consumption in reverse osmosis (RO) desalination processes and to identify those with the greatest potential for reduction. Specific energy consumption (SEC), in kWh per m^3 of permeate production, is due to the retentate osmotic pressure, the resistance to fluid permeation through the membrane, the friction losses in the retentate and permeate channels of the spiral wound membrane (SWM) modules and the non-ideal operation of high pressure pumps and energy recovery devices (ERD). Taking advantage of a recently developed SWM-module performance simulator, the aforementioned individual contributions to SEC are determined for two case studies, typical of seawater and brackish water desalination processes, for steady state operation. Detailed results are obtained with SEC itemized per SWM element in a typical 7-element pressure vessel. Comparative assessment of the results is enlightening, showing that the greatest margin for the desirable SEC reduction is related to improvements of membrane permeability and efficiency of pumps and ERD. The indirect, yet significant, effect of other key design and operating process parameters is also discussed.

1. Introduction

The specific energy consumption (SEC), in kWh per m^3 of product water, is the single most important parameter characterizing the performance of the desalination process [1], particularly from the standpoint of overall process sustainability [2]. SEC is comprised of contributions from the operation of the various sections of an entire membrane desalination plant; i.e. (1) the feed-water intake facility, (2) the pre-treatment section, (3) the main desalination section (that includes high-pressure pumps, RO membrane trains and energy recovery devices [ERD]), (4) the product post-treatment section and (5) the brine treatment/disposal facility [3]. The largest contribution to SEC, usually varying between 60% and 80% (depending on feed-water type, local conditions, technology employed) is due to the *main section* where the membrane desalination process is carried out [4,5]. This section, on which this paper is focused, also exhibits the greatest potential for SEC reduction, as will be discussed in the following.

In the typical desalination process considered here (including pumps, RO membrane trains and ERDs), energy is consumed to overcome the retentate osmotic pressure, the resistance to fluid permeation through the membrane, the friction losses in the retentate and permeate channels of the spiral wound membrane (SWM) modules as well as loses due to the non-ideal operation of high pressure pumps and energy recovery devices (ERD). With the exception of the thermodynamically imposed minimum SEC [6], related to the feed-fluid osmotic pressure, the contribution to SEC from other factors can be controlled (at least to some extent) and minimized through improvements in equipment and process design and operation [3–5]. Therefore, it is of great interest to comparatively assess these contributions and to identify those factors with the greatest potential for SEC minimization through appropriate improvements, mainly in equipment and process design. Such information is most useful for techno-economic design studies of RO plants, for prioritization of related R & D activities as well as for environmental-impact and overall sustainability studies of desalination projects [2]. Regarding the latter studies, it is needless to stress the direct relation of SEC with the environmental burden due to the desalination plant operation.

There are quite a few published studies dealing with the contributions to SEC in RO plants which are summarized in recent papers. Two types of such papers can be identified; i.e. those based on data from operating plants (e.g. [1,7,8]) and other employing theoretical analysis [9–13]. Although the former type of data are useful, they usually provide itemized energy consumption values averaged in operating time (over an undefined range of process conditions), often with incomplete supporting data on process design and operating conditions. The existing theoretical-type studies, to the best of the authors knowl-

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edge, present relevant energy consumption data either in general terms, in the context of comprehensive optimization formulations [9,10,12], however lacking adequately detailed analysis of itemized contributions to SEC [13], or provide such contributions in unclear terms and with inadequate information on the computational method employed [11].

This work aims to present an analysis of contributions to SEC, through two typical case studies of RO membrane desalination of sea and brackish water. The analysis is largely made by employing an advanced comprehensive software tool, permitting performance simulation of an entire (multi SWM element) pressure vessel of RO plants, operating under steady state conditions [14,15,16]. With this software, the spatial distribution of all process parameters (throughout a vessel) is predicted [15,16] thus facilitating various types of reliable parametric studies, including those of the present paper. In the following, basic theoretical considerations are outlined first. Computational results, for the two case studies, already documented [16], are revisited and relevant data are re-cast in a form catering to the needs of the present analysis. Finally, a comparative assessment of various contributions to SEC is made, leading to useful conclusions.

2. Theoretical background

2.1. SEC in a typical membrane desalination process

Fig. 1 shows schematically a typical single stage desalination process, including concentrate-energy recovery by ERD. In addition to the variables marked in the process diagram of Fig. 1, the following parameters are defined:

By employing an energy balance over the entire process (outlined in the Supplement) one obtains a general expression for the *Specific Energy Consumption* (*SEC*), defined in Eq. (1) and expressed in terms of main process parameters in Eq. (2):

$$\mathrm{SEC} = \frac{W_{TOTAL}}{Q_P} \tag{1}$$

$$\mathrm{SEC} = \frac{1}{R}\left[\frac{P_f - P_o}{\eta}\right] + (1-\beta)\left[\frac{1-R}{R}\right]\left[\frac{P_o + \eta_E \Delta P - \eta_E P_f}{\eta}\right] \tag{2}$$

where, in addition to variables depicted in Fig. 1, R is the permeate recovery fraction and η the composite efficiency of pumps, i.e. the product of hydraulic, electrical motor and variable frequency drive efficiency as subsequently discussed. For the case of "*ideal*" *operation of pumps and pressure-equipment* (i.e. $\beta = 0$, $\eta = \eta_E = 1.0$), the specific energy consumption under ideal conditions $\mathrm{SEC_i}$ is given as:

$$\mathrm{SEC_i} = \left(\frac{1-R}{R}\right)(\Delta P) + (P_f - P_o) \tag{3}$$

Therefore, energy losses due to the inefficiencies in pump and ERD operation are obtained from the difference of Eq. (2) minus Eq. (3);

$$\mathrm{SEC_{inef}} = \mathrm{SEC} - \mathrm{SEC_i} \tag{4}$$

It will be noted that SEC is readily computed in Pascal or kWh/m^3, with a conversion factor 1.0 kWh/m^3 ≈ 3.6 × 10^6 Pa. Further, it should be pointed out that in the present treatment, two simplifications will be made, with no loss of generality; i.e. that a) the feed water pressure at the pumps suction, as well as the permeate and concentrate discharge pressures are at the same reference value P_o (Fig. 1), and b) pressure drop in the interconnecting piping in the membrane trains will be ignored.

2.2. Itemized contributions to SEC

The particular contributions to SEC in the main desalination section (of an entire plant) are due to the physico-chemical and transport phenomena taking place within the several SWM modules, arranged in series in the pressure vessels, that comprise the main desalination facility. For a single stage operation considered here, suffice it to determine SEC in a single pressure vessel, schematically shown in Fig. 1.

Under steady state conditions (i.e. in the case of constant feed conditions as well as membrane properties) there is a spatial variation of all process parameters throughout the membrane sheets comprising the SWM modules. Recently, an advanced simulation tool has been developed in the authors laboratory [14,15,16] capable of predicting the spatial variation of all key parameters of interest (*including local pressures and species concentrations)*, necessary to determine the required itemized SEC contributions. The case study results reported here will be based on the stock of data obtained in parametric studies, already reported [16] for the *constant recovery* mode of operation of the desalination process. It will be added that in the analysis underpinning

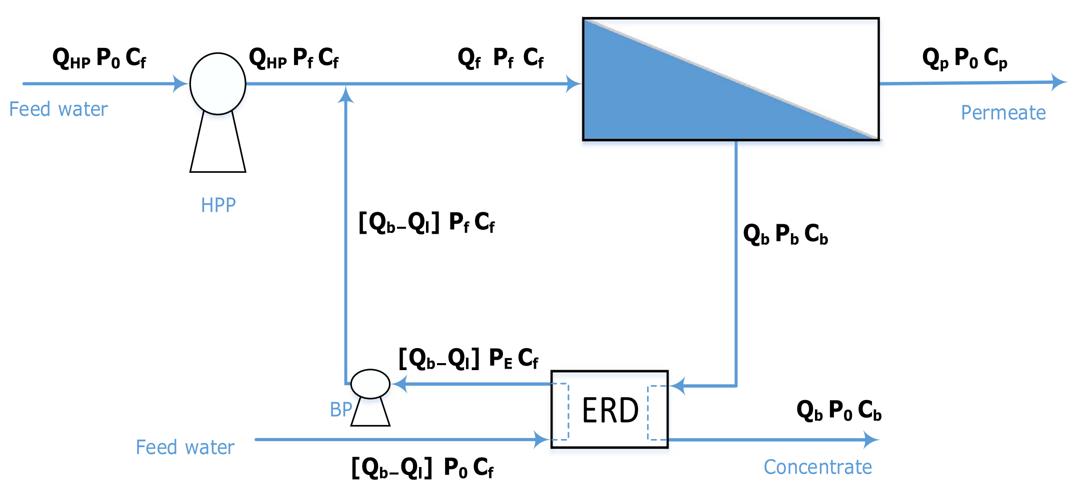

Fig. 1. Schematic of a single-stage membrane desalination unit with energy recovery device (ERD).

Pressure difference across pressure vessel	$\Delta P = P_f - P_b$
Pressure transfer efficiency of ERD	$\eta_E \approx \frac{P_E}{P_b}$
Leakage ratio of ERD	$\beta = \frac{Q_l}{Q_b}$

the process simulator development [14] flat sheet membrane envelopes are considered with planar (x, y) variability of all parameters.

Regarding the SWM modules, the main variables of interest here are the pressure at retentate and permeate side P_R and P_P, respectively, the bulk and wall concentration of salts (C_b and C_w) at the retentate side (responsible for the respective osmotic pressure of retentate) and the local permeate flux distribution J. The contributions to SEC described in the following, will be expressed with respect to the total permeate flow rate Q_P, at the outlet of a pressure vessel. However, contributions to SEC can be also obtained per SWM module to get insights into the variability of these parameters along the pressure vessel. The computational scheme employed [15,16] involves finite volume elements with corresponding finite membrane surface element ΔA; thus, the flux distribution values J_i correspond to local permeate flow rates $Q_{Pi} = J_i\,\Delta A$.

2.2.1. Energy consumption to overcome osmotic pressure, SEC_{os}

This item of energy consumption is expressed as:

$$SEC_{os} = \frac{\sum_{i=1}^{N} Q_{Pi}\,\Delta\pi(C_{wi})}{Q_P} \tag{5}$$

where $\Delta\pi(C_{wi})$ is the effective osmotic pressure difference computed with the local wall concentration C_{wi} due to polarization phenomena. The negligible osmotic pressure of permeate is ignored for simplicity. One can also compute a theoretical minimum SEC_{min} corresponding to osmotic pressure of the bulk fluid, of concentration C_b; i.e. using in Eq. (5) the osmotic pressure distribution $\Delta\pi(C_{bi})$ instead of $\Delta\pi(C_{wi})$. Therefore, the expression

$$SEC_{CP} = SEC_{os} - SEC_{min} \tag{6}$$

provides a fair estimate of energy consumption due to concentration polarization, SEC_{CP}.

2.2.2. Energy consumption due to filtration SEC_f

This contribution to SEC represents energy losses to overcome the membrane resistance to fluid permeation; it depends on the spatial distributions of local trans-membrane pressure (TMP) and of the local effective osmotic pressure; i.e.

$$SEC_f = \frac{\sum_{i=1}^{N} Q_{Pi}\,[P_{Ri} - P_{Pi} - \Delta\pi(C_{wi})]}{Q_P} \tag{7}$$

However, this quantity is directly affected by the membrane permeability or resistance R_m which essentially determines the local flux J_i and Q_{Pi} through a Darcy type expression; i.e.

$$Q_{Pi} = \frac{[P_{Ri} - P_{Pi} - \Delta\pi(C_{wi})] \times \Delta A}{\mu \times R_m} \tag{8}$$

where μ is the water viscosity. It should be further noted here that fouling in the retentate channels affects directly SEC_f through an additional fouling resistance R_c [17] and indirectly through the reduction of the trans-membrane pressure term in the numerator of Eq. (7), which necessitates an increase of the feed pressure $P_f = (P_R)_{inlet}$ to maintain a constant permeation rate Q_{Pi}. This significant issue will be discussed in following Section 4.

2.2.3. Energy consumption due to friction losses in SWM module channels, SEC_R and SEC_P

The specific energy consumption due to flow friction losses in the retentate and permeate channels is designated as SEC_R and SEC_P, respectively. These quantities depend on the spatially varying flow fields in the retentate and permeate channels, and they are determined through local data (by analogy to the aforementioned similar quantities) as

$$SEC_R = \frac{\sum_{i=1}^{N} Q_{Ri} \times \Delta P_{Ri}}{Q_P} \tag{9}$$

$$SEC_P = \frac{\sum_{i=1}^{N} q_{Pi} \times \Delta P_{Pi}}{Q_P} \tag{10}$$

Here the flow rates Q_{Ri} and q_{Pi} (as well as the respective pressure differences) are the average values (in each computational cell) along the principal flow direction (x and y) in the retentate and permeate channel, respectively.

The graphs included in the Supplement (Fig. S2–S4), for the brackish and seawater cases considered here, show typical examples of the spatial (x, y) distribution of key process parameters, throughout membrane sheets. Such data, in discretized form, have been used to compute the itemized SEC contributions, according to the above Eqs. (7) to (10).

3. Results of case studies

Results of itemized SEC contributions are reported from two realistic case studies corresponding to RO membrane desalination of sea- and brackish-water. Parametric study results, for these two general cases, to assess the effect of alternative SEM designs (mainly membrane sheet number/width and feed-spacer geometry) have already been reported [16] for *constant recovery* operation. The computational results from those detailed SWM module performance simulations were revisited and the above-mentioned particular SEC contributions were determined. The input data for the case studies, listed in Table 1 for convenience, represent conditions and module design parameters fairly typical of those encountered in practice.

The itemized contributions to SEC for the sea and brackish water cases are computed for each SWM module of the 7-element pressure vessel and listed in Table S1 in the Supplement. Moreover, in the Supplement, axial variation of retentate-side friction losses across a pressure vessel (Fig. S1) as well as typical spatial distributions of key parameters (Figs. S2–S4) throughout the pressure vessel are provided, for the studied cases. In Table 2, the results on SEC contributions are summarized for both case studies (sea- and brackish- water). For convenience, pie charts for each case are presented in Figs. 2 and 4. Energy losses due to high pressure pumps are computed by considering an overall efficiency $\eta = 0.85$, obtained as follows:

$$\eta = \eta_{hydr} \cdot \eta_{motor} \cdot \eta_{VFD} \tag{11}$$

where the respective hydraulic pump, electrical motor and variable speed drive efficiency values $\eta_{hydr} = 0.90$, $\eta_{motor} = 0.96$ and $\eta_{VFD} = 0.98$ [18] are typical of the performance of modern pumping systems. Regarding ERDs, state of the art equipment efficiency $\eta_E = 0.95$ and leakage ratio $\beta = 0.02$ [19] are used in the computa-

Table 1
Input data employed for the case studies.

Feed water characteristics	Brackish	Seawater
Salinity	2,000 ppm	40,000 ppm
Operating parameters		
Feed flow rate, Q_f	10 m^3/h	10 m^3/h
Recovery, R	70%	50%
Module design parameters		
Membrane resistance, R_m	$0.9 \times 10^{14}\ m^{-1}$	$3.04 \times 10^{14}\ m^{-1}$
Membrane area of module, A	37 m^2	
Number of envelopes, N	15	
Membrane sheet length, L	0.96 m	
Membrane sheet width, W	A/(2 × N × L) m	
Retentate spacer geometry	L/D = 8, β′ = 90°	
Retentate channel gap, h_R	0.71 mm (28 mil)	
Permeate channel gap, h_P	0.23 mm	
Permeate spacer lateral permeability, k	$2.0 \times 10^{-10}\ m^2$	

Table 2
Itemized contributions to SEC of RO process (η = 0.85, η_e = 0.95, β = 0.02).

Itemized SEC, kWh/m^3	Sea-water	Brackish water
SEC_f membrane filtration resistance	0.574	0.194
SEC_R friction losses, retentate	0.057	0.036
SEC_P friction losses, permeate	0.0012	0.0016
SEC_{min} osmotic pressure	1.200	0.074
SEC_{CP} concentration polarization	0.057	0.005
SEC_{inef} pump & ERD inefficiency	0.485	0.068
Total SEC	2.374	0.378

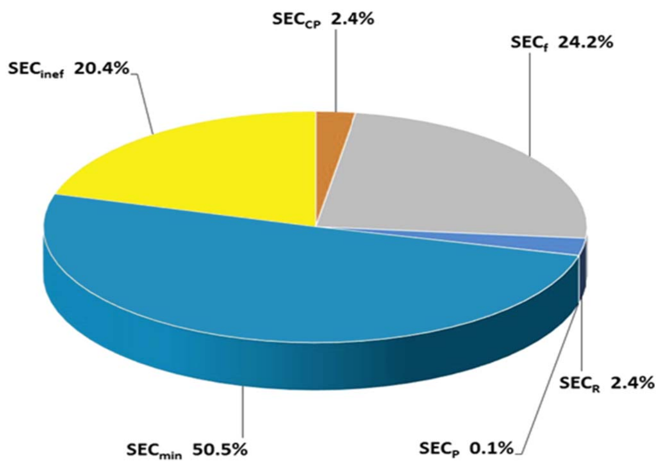

Fig. 2. Sea-water RO desalination process at steady state operation. Itemized percentage contributions to Specific Energy Consumption; total RO process SEC = 2.374 kWh/m^3.

tions.

The data depicted in Fig. 2 confirm the well-known significance of osmotic pressure effects on energy consumption; i.e. for this case study of seawater desalination, SEC_{min} = 1.2 kWh/m^3, which corresponds to 50.5% of the total SEC of the process. However, it is interesting that the direct contributions to SEC due to flow frictional losses in both membrane channels and to concentration polarization (for 8-inch SWM modules, commonly employed today) are relatively insignificant; i.e. at the level of 2.5% of SEC for the main desalination section. This percentage is even lower if one adds to SEC the contributions from other sections of the plant; i.e. from intake, pretreatment and post treatment sections. It is clear that the two other contributions due to pumps and ERD non-ideal performance (SEC_{inef}) and fluid filtration through the membrane (SEC_f) are of particular significance and at roughly the same level (~20% to 24%); these quantities also present the greatest potential for energy savings, as subsequently discussed.

The total specific energy consumption in the main desalination process for sea water, determined by summing up the itemized contributions, is SEC = 2.374 kWh/m^3 (Table 2). This value is in fair agreement with the value (SEC = 2.39 kWh/m^3) obtained directly through the overall energy balance (Eq. (1)), thus lending support to the reliability of the present analysis. Additionally, the SEC value (2.374 kWh/m^3) computed here for the main process of a sea-water RO plant is fairly close to that reported [8] for similar industrial plants (i.e. SEC = 2.54 kWh/m^3) considering also that a small contribution to SEC due to friction losses in interconnecting plant piping has not been accounted for in this study.

Fig. 3a shows the variation of itemized SEC contributions for each SWM module along the pressure vessel, for *sea water* desalination. The effect of drastically decreasing *effective driving force* for fluid permeation [i.e. $P_R - P_P - \Delta\pi(C_w)$] tends to reduce the SWM elements' productivity downstream, the mean permeate flow rate per SWM module Q_P, and consequently the respective contributions to SEC. Fig. 3b presents for each SWM element the variation of total SEC (with the exception of

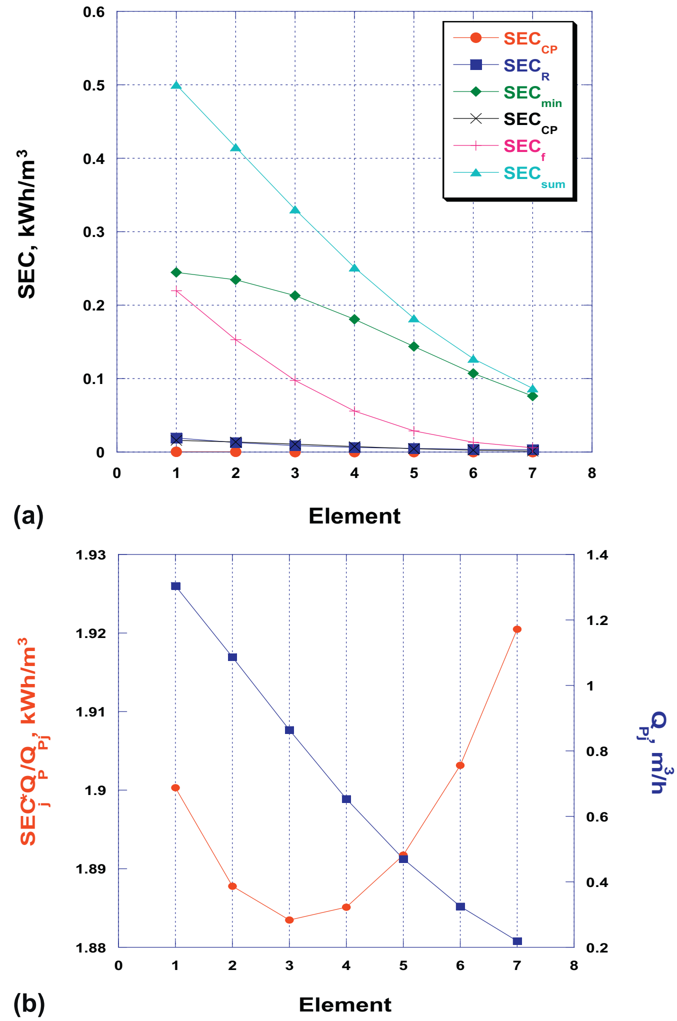

Fig. 3. Sea-water RO desalination process; SEC per SWM element. (a) Itemized contributions to SEC. (b) Specific Energy Consumption (excluding SEC_{inef}) per unit flow rate of permeate produced in each SWM element, Q_{Pj}. Index j (1 to 7) designates the position of a SWM element in the pressure vessel.

SEC_{inef}) *per unit flow rate of permeate produced in the same SWM element*, Q_{Pj}; the quantity Q_{Pj} (j = 1 to 7) actually designates the SWM element productivity. As shown in Fig. 3b, despite the fact that the differences from the mean (1.89 kWh/m^3) are not very significant, there is a tendency *for increase* of that quantity at the tail elements due to their low productivity Q_{Pj}.

Turning to *brackish water* desalination, Table 2 and Fig. 4 reveal a very different total value and distribution of various SEC components, compared to sea water desalination plant. Specifically, the total SEC is almost an order of magnitude smaller than that for seawater desalination, due to the much smaller salt concentration and corresponding osmotic pressure. Further, it is interesting that the energy losses due to membrane resistance SEC_f account for half of SEC (under the conditions of this case study), with much reduced SEC_{min} due to relatively small osmotic pressure. The contribution of pump and ERD inefficiencies are still significant, whereas that due to friction losses in the retentate channels SEC_R tends to become substantial (~10%). Despite the generally small energy consumption for this low salinity feed-fluid, improved membrane permeability appears to offer the most significant potential for reduction, and to a lesser extent reduced pump/ERD inefficiencies and friction losses at the retentate side.

In Fig. 5a one observes that the itemized contributions to SEC per SWM module are somewhat more uniform compared to the seawater case; this is attributed to the more uniform (or balanced) permeate

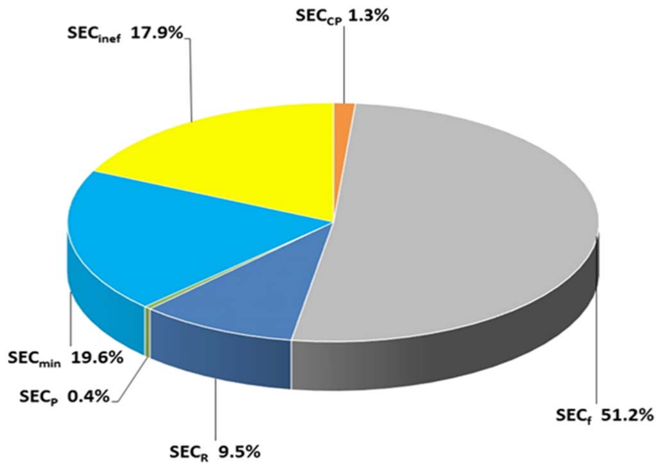

Fig. 4. Brackish-water RO desalination process at steady state. Itemized percentage contributions to Specific Energy Consumption; total RO process SEC = 0.379 kWh/m^3.

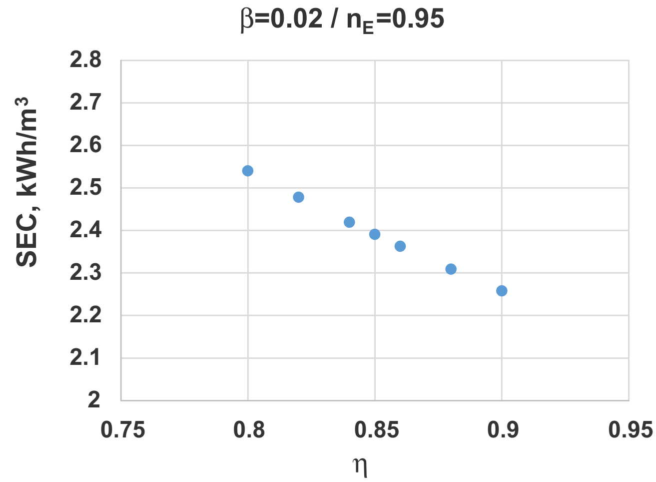

Fig. 6. Sea water. SEC as a function of composite pumps efficiency η.

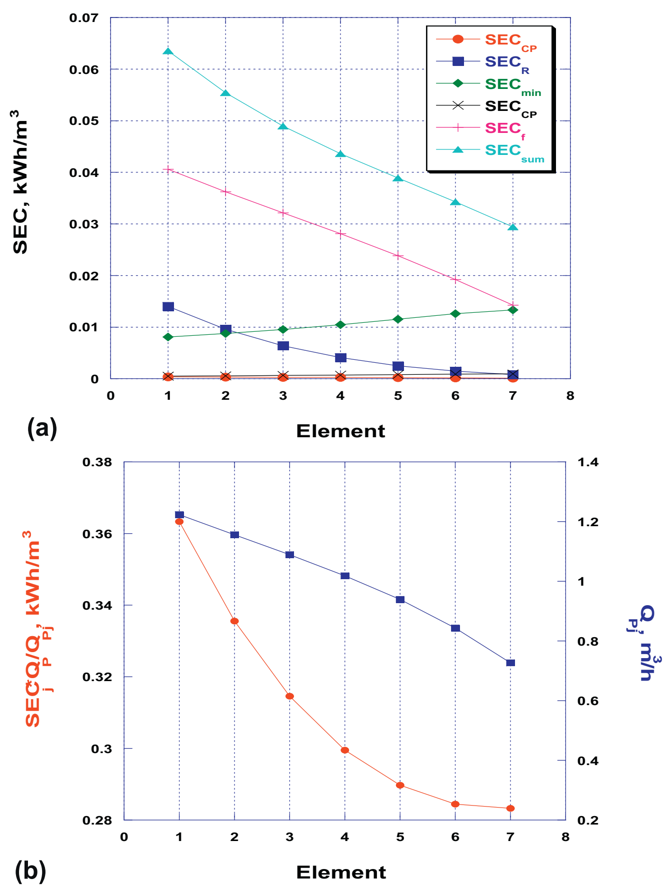

Fig. 5. Brackish water RO desalination process; SEC per SWM module. (a) Itemized contributions to SEC. (b) Specific Energy Consumption (excluding SEC_{inef}) per unit flow rate of permeate produced in each SWM element, Q_{Pj}. Index j designates the position of a SWM element in the pressure vessel.

productivity per element, which of course decreases downstream.

For the same reason, as shown in Fig. 5b, there is a *monotonic* (yet modest) reduction of energy consumed in each SWM element per unit flow rate of permeate produced in the same element, Q_{Pi}, unlike the case of sea-water where it tends to increase (Fig. 3b).

4. Discussion

The effect of feed water salinity on SEC is dominant, as is well-known; indeed, although the relationship is not linear, order of magnitude reduction of salinity leads to similar magnitude SEC reduction. Therefore, ongoing efforts to desalinate "diluted" saline waters (e.g. by mixing sea-water with lower salinity surface waters, as well as with treated effluent streams) are well justified. Such efforts are ongoing and have already been apparently successfully demonstrated (e.g. [20]). Regarding *low salinity feed-waters*, it appears that energy losses due to filtration SEC_f are a dominant component, over all other contributions to total energy losses; i.e. membrane permeability should be a prime concern in respect of both salt rejection and energy losses. Of smaller magnitude but significant are the contributions due to pressure equipment inefficiencies [SEC_{inef}] and friction losses in the retentate channels [SEC_R].

For *high salinity feedwater*, two areas deserving particular attention for reduction of SEC are a) improved efficiencies of high pressure pumps and of ERD equipment and b) membranes with improved permeability. The former effect is striking, as additionally shown in Fig. 6 where total SEC is plotted versus the composite pumps efficiency, for seawater desalination; a similar graph for brackish water desalination is provided in Fig. 5S (Supplement). By contrasting data in Table 2 with those in Fig. 6 (for sea-water desalination), it is observed that increasing the pumps efficiency only by 2% leads to energy savings roughly equal to (or even greater than) the energy consumption due to total fluid friction losses in the retentate channels across the pressure vessel. Regarding energy losses due to permeate filtration, SEC_f, the ongoing efforts [21,22,23] to reduce membrane permeability while maintaining a high level of salt rejection can pay off.

Improving membrane permeability has a direct impact on feed pressure P_f reduction and thus on SEC_f; moreover, by reducing P_f, proportional reduction is achieved of energy losses due to pressure equipment inefficiencies SEC_{inef}. It should be stressed, however, that the retentate osmotic pressure poses limitations to benefits resulting from permeability improvements. For example, for feed water with 40 g/L salt concentration, the retentate osmotic pressure at 50% recovery is at the level of 54 bar, thus significantly reducing the margin for feed pressure reduction. Among alternative approaches to reduce energy consumption, through reduction of feed pressure, a two-stage operation has been proposed [11,23], whereby the first stage (treating the input feed-water of higher flow rates) can operate at significantly lower feed pressure; this is permissible because of the relatively smaller fluid osmotic pressure in the leading SWM elements. However, the issue of selecting process schemes (i.e. whether of single or two-stage type, seven- or eight-SWM module pressure vessels, other), can be resolved through a multi-criteria optimization (e.g. [9,10,12]), involving (in addition to SEC) decision variables related to overall sustainability [2] i.e. product-water cost and environmental-impact indices. Moreover, in

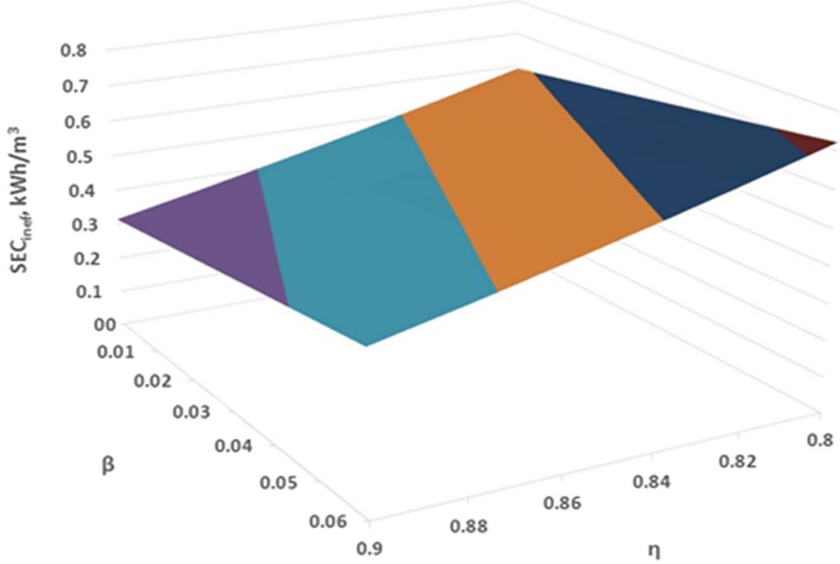

Fig. 7. Sea water. SEC_{inef} as a function of efficiency parameters β and η; η_E = 0.95.

a comprehensive desalination-process optimization, one should consider at the outset other key project objectives, limitations and local conditions; e.g. boron removal, feed water composition and variability, available electric power and tariff variability [9,10,12].

The efficiency of pumps and of ERD obviously have a very significant effect on the total SEC. The main efficiency-parameter values employed in this assessment, i.e. $\eta = 0.85$, ($\eta_{hydr} = 0.90$, $\eta_{motor} = 0.96$, $\eta_{VFD} = 0.98$) $\eta_E = 0.95$ and leakage ratio $\beta = 0.02$ are typical of modern equipment [18,19], and are probably at the high side. Indeed, there are RO desalination units (especially of relatively small capacity) likely operating under worse pump efficiencies. In fact, the greater efficiency of high-pressure pumps in large plants (leading to somewhat reduced SEC_{inef}), compared to that for small RO units, could be an indicator for differentiating between the two types of plants, aside from other differences; e.g. increased product-water unit cost for the small plants due to greater contribution of capital expenses. Results of some SEC_{inef} parametric calculations, by varying pumps composite efficiency η and leakage ratio β, plotted in Fig. 7 for sea-water (and in Fig. S6, Supplement for brackish water), show the level of sensitivity of SEC within typical ranges of these parameter values. Moreover, they suggest that the general trends identified and conclusions drawn in this *comparative assessment* (regarding itemized contributions to SEC) are sound as they are based on a set of realistic pump/ERD efficiency values. Finally, it should be noted that the use of ERD in brackish-water RO plants, especially in the older and smaller ones, is uncommon; indeed, using conventional economic criteria, the use of ERDs in such plants may not be attractive. However, in new brackish-water plants, employing Life Cycle cost analysis, the use of ERDs (of the type and efficiency considered here) is justified and such devices are successfully employed [24].

Another significant topic in designing and operating desalination plants, with direct and indirect impact on energy consumption, is the design of SWM elements, and in particular the *optimization of membrane envelope number* (*or width*) and *of feed-spacer geometrical characteristics* [25,26], for a fixed external SWM-element diameter. It is well-documented that fewer envelopes of longer width are associated with greater spatial non-uniformity of transmembrane pressure and of flux, entailing greater feed pressure to achieve a certain/fixed water recovery [15,16], with obvious negative impact on SEC. Feed-spacer geometry also impacts on friction losses and concentration polarization in the feed-channels [15,16]; moreover, there is evidence (e.g. [27]) that it affects membrane *fouling phenomena*.

In the light of the present results, it appears that the direct and indirect effects due to fouling may be more important compared to energy consumption components SEC_R and SEC_P. Indeed, an increase of the effective membrane resistance due to fouling can cause a substantial increase of SEC_f and of SEC_{CP}, which lead to increased feed pressure (required for constant recovery processes) and in turn to an increase of energy losses primarily due to pressure-equipment inefficiencies SEC_{inef}. It will be also recalled that SEC_{CP} can additionally increase due to Cake Enhanced Osmotic Pressure (CEOP) mechanism [28]. To get an idea of the direct detrimental effect of fouling on energy consumption, one can estimate (through Eq. (3)) the increase of SEC due to fouling $\Delta(SEC)_{fouling}$ under *ideal* pressure-equipment operation, i.e. $\eta = \eta_E = 1.0$, $\beta = 0$:

$$\Delta(SEC_i)_{fouling} = (P_f)_{fouling} - (P_f) + [(1–R)/R][(\Delta P)_{fouling} - \Delta P] \qquad (12)$$

For instance, for the seawater desalination case considered here, a 10% increase of feed pressure P_f due to fouling (not uncommon in RO plants) has a significant effect, leading to an increase of SEC_i greater than 0.2 kWh/m^3.

In closing, although the foregoing case study results tend to emphasize the significant direct effect of membrane permeability and pump/ERD inefficiencies on SEC, the importance of structural characteristics of the SWM module (in particular the feed-spacer geometric properties and the membrane envelope number or width) should not be underrated. Indeed, as discussed in more detail elsewhere [25,26], both types of parameters affect the pressure fields in the retentate and permeate membrane channels, thus the transmembrane pressure spatial distribution, and in turn the flux distribution and SWM module productivity. Additionally, the significant effect of these properties (especially of retentate-side spacers) on the evolution of fouling is undisputed. However, significant aspects of SWM module fouling remain unclear and more work is needed to clarify them [17] and to enable development of a comprehensive dynamic simulation tool capable of predicting the RO plant performance and the increase of SEC due to fouling. Systematic steps in that direction have been reported recently [29].

5. Conclusions

The contributions of several clearly defined factors to the Specific Energy Consumption (SEC) of the main RO desalination process are quantified, for two typical cases of sea and brackish feed-water, under conditions of *constant permeate recovery*. Using recently developed advanced comprehensive software, the itemized contributions to SEC per SWM module, in a seven-element pressure vessel, have been determined. The significant effects on SEC of *membrane permeability* and *inefficiencies* of pumps and ERD are clearly demonstrated, suggesting that priority should be placed on relevant R & D work, aiming to achieve substantial SEC reduction. The effect of SWM-module design parameters (mainly retentate spacers and membrane envelope number/width) on SEC is more subtle; i.e. although the *direct* effect of these parameters on membrane-channel friction losses is relatively small, the *indirect* effect on spatial flux distribution, that tends (under some conditions) to reduce SWM-module productivity, could be more important. In such cases, maintaining constant recovery, leads to feed-pressure increase and concomitant SEC increase due to pump/ERD inefficiencies. Similarly, these structural SWM module parameters seem to affect the detrimental membrane fouling evolution, although this issue requires more careful R & D work. The aforementioned comparative assessment, of the itemized SEC contributions, is made by considering the thermodynamic constraints posed by the feed- and retentate-fluid osmotic pressure. As expected, the contribution of the thermodynamically imposed SEC_{min} to the total SEC is large in the case of seawater desalination but of secondary importance in the case of brackish water.

List of symbols

C_W	Salt concentration at the membrane surface
(C_{Wi})	Local salt concentration at membrane-surface element ΔA
C_b	Salt concentration in the retentate bulk
J_i	Local flux at membrane-surface element ΔA
P_f	Feed pressure
P_b	Concentrate pressure
P_o	Permeate pressure
P_{Ri}	Local retentate-side pressure
P_{Pi}	Local permeate-side pressure
Q_f	Feed flow rate
Q_l	Leakage flow rate in ERD
Q_P	Total permeate flow rate
Q_{Pi}	Local membrane-permeation flow rate ($= J_i\,\Delta A$)
Q_{Ri}	Local retentate flow rate
q_{Pi}	Local flow rate in the permeate channel
R	Desalinated water recovery
R_m	Clean membrane resistance
R_c	Membrane fouling resistance
SEC	Specific energy consumption
SEC_i	SEC under ideal conditions; i.e. zero inefficiency of pumps and ERD
SEC_{inef}	SEC due to non-ideal pump and ERD operation
SEC_{OS}	SEC to overcome osmotic pressure
SEC_f	SEC due to membrane filtration resistance
SEC_R	SEC due to fluid friction losses in the SWM module retentate channels
SEC_P	SEC due to fluid friction losses in the SWM module permeate channels
SEC_{min}	SEC to overcome the osmotic pressure of the bulk fluid
SEC_{CP}	SEC due to concentration polarization
W_{total}	Total hydraulic power
β	Leakage ratio of ERD
$\Delta\pi(C_W)$	Osmotic pressure difference across the membrane
ΔP	Pressure difference across pressure vessel
ΔA	Membrane surface element for local computations
ΔP_{Ri}	Local pressure difference at the retentate channel
ΔP_{Pi}	Local pressure difference at the permeate channel
η_E	Pressure transfer efficiency of ERD
η	Overall pump efficiency
η_{hydr}	Hydraulic pump efficiency
η_{motor}	Electrical motor efficiency
η_{VFD}	Variable frequency drive efficiency
μ	Water viscosity

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2017.04.006.

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