Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.939489

55 (2015) 2562–2572
August

Taylor & Francis
Taylor & Francis Group

A design method of the RO system in reverse osmosis brackish water desalination plants (calculations and simulations)

E. Ruiz-Saavedra[a,*], A. Ruiz-García[b], A. Ramos-Martín[c]

[a]*CAFMA Research Group, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria. Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain, Tel. +34 928 459629; Fax: +34 928 451872; email: enrique.ruiz@ulpgc.es*

[b]*Departamento de Ingeniería Civil, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria. Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain*

[c]*Departamento de Ingeniería de Procesos, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria, Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain*

Received 24 March 2014; Accepted 16 June 2014

ABSTRACT

This paper proposes a simple design method of the RO system in RO brackish water desalination plants. This method is based on the application of maximum available recovery without scaling of any of the compounds present in the water as silica, calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate, and calcium fluoride, and membrane manufacturer design guidelines, and the plant production. It is a continuation of the paper "A design method of the RO system in reverse osmosis brackish water desalination plants (procedure)" presented at the conference on Membranes in Drinking and Industrial Water Production, Leeuwarden, The Netherlands, 10–12 September 2012. Although the method was originally conceived for application to subterranean brackish waters in the Canary Islands, Spain (principally Gran Canaria, Fuerteventura and Tenerife), it can be extrapolated to other types of region and water treatable with RO systems. The required input data are the chemical composition of the feed water, pH, temperature, SDI, membrane manufacturer design guidelines, and the plant production. The programmed method determines the design of the RO system (arrangement) and the operating pressure so as the quality of the product water for different operating years and different types of the RO elements. The method whose procedure is described graphically and analytically can be used as an aid in design optimization of RO brackish water desalination plants with acid-free pre-treatment processes and by the use of scale inhibitor using spiral wound membranes. Practical applications are presented. Calculations and simulations for different types of feed water and capacities are showed. A comparison between the values obtained by this method and from membranes manufacturer software is shown so as the comparison between these and the real values from different desalination plants.

*Corresponding author.

Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

Keywords: Brackish water; Reverse osmosis; Desalination plants; RO system design

1. Introduction

This paper describes a simple design method of RO system in BWRO desalination plants with just asticalants as a pretreatment. The required input data are the chemical composition of the feed water, pH, temperature, SDI, membrane manufacturer design guidelines, and the plant production. The programmed method determines the design of the RO system according to Fig. 1.

A part of this RO system design is based over operational experience in BWRO desalination plants in Canary Islands.

Although this method uses Filmtec FT30 spiral wound membranes [1], it can be extended to other similar spiral wound membranes types.

The following considerations were made in the preparation of this paper:

(1) Use of specific scale inhibitors for $CaCO_3$, $CaSO_4$, $BaSO_4$, $SrSO_4$, and CaF_2.
(2) For economic reasons, namely their high cost, the authors did not consider the use of silica scale inhibitors.
(3) The temperature of the reject water is the same as that of the feed water, namely between 10 and 30˚C (well brackish water temperature range in Canary Islands).
(4) The reject water pH value is lower than 8.3. On the one hand, this is equivalent to considering the feed water pH to be lower than 8, and on the other hand considering total alkalinity ($[HCO_3^-] + 2[CO_3^{2-}] + [OH^-]$) to be practically all due to bicarbonate ions [2].
(5) Use of spiral wound membranes (Filmtec FT30 or similar) of 40´´ length and 4´´ & 8´´ diameter.
(6) RO elements per pressure vessel from 1 to 6.
(7) Range of RO system recovery from 10% (minimum) to 87% (maximum).
(8) Production capacities lower than 2.5 m^3/day are not considered.
(9) Maximum salinity of the feed water (brackish) was 15,000 mg/l and maximum salts concentration of the reject water was 18,000 mg/l.

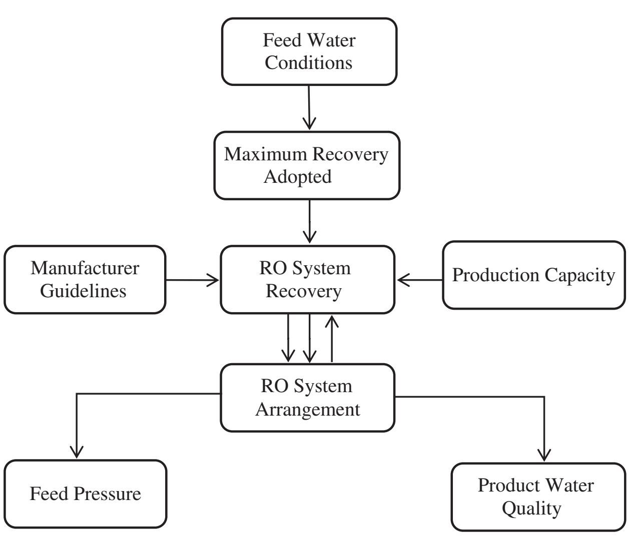

Fig. 1. Procedure.

2. Procedure

According to Fig. 1:

From the chemical analysis of the water to be treated, as well as its temperature and pH we calculate the maximum recovery to be adopted ($R_{\text{max-adopt}}$) for there to be, along with no silica or calcium carbonate or calcium sulfate or barium sulfate or strontium sulfate or no calcium fluoride scaling [3–9].

With the $R_{\text{max-adopt}}$ value and with the production capacity (m^3/day) and using the manufacturer guidelines, the RO system recovery (R_{RO}) and the RO system arrangement for 4´´ and 8´´ RO elements are calculated [10].

From the RO system arrangement and according to the solution-diffusion model, the performance of a specified RO system using the membrane type m is defined by the following transport equations relating to the RO element i [11,12]:

- Permeate flow through the RO element i (Qw_{mi}):

$$Qw_{mi} = Kw_{mi}(Pd_{mi} - \pi d_{mi})S_{mi} \quad (1)$$

where Kw_{mi} is the water permeability coefficient of the membrane m of the RO element i, Pd_{mi} is the differential pressure across the membrane m of the RO element i, πd_{mi} is the differential osmotic pressure across the membrane m of the RO element i, and S_{mi} is the membrane surface of the RO element i.

- Salt flow through the RO element i (Qs_{mi}):

$$Qs_{mi} = Ks_{mi} \cdot Cds_{mi} \cdot S_{mi} \tag{2}$$

where Ks_{mi} is the salt permeability coefficient of the membrane m of the RO element i, Cds_{mi} is the differential salt concentration across the membrane m of the RO element i, and S_{mi} is the membrane surface of the RO element i.

The term $(Pd_{mi} - \pi d_{mi})$ of Eq. (1) is the net or effective pressure on the RO element i ($Pnet_i$) and can be expressed as follows:

$$Pnet_i = P_{fi} - \frac{\Delta P_{fri}}{2} - P_{pi} - (\pi_{fri} - \pi_{pi}) \tag{3}$$

where P_{fi} is the feed pressure of the RO element i, ΔP_{fri} is the feed-reject pressure drop of the RO element i, P_{pi} is the permeate pressure of the RO element i, π_{fri} is the osmotic pressure of the feed-reject average concentration of the RO element i, and π_{pi} is the osmotic pressure of the permeate concentration of the RO element i. Given that π_{fri} can be expressed in the following form:

$$\pi_{fri} = \pi_{fi} \cdot RF_i \cdot CP_i \tag{4}$$

where π_{fi} is the osmotic pressure of the feed concentration of the RO element i, RF_i is the recovery factor of the RO element i, and CP_i is the concentration polarization value in the RO element i.

Given that the salt rejection of the RO element i (SR_i) can be expressed as an integer of the following form:

$$SR_i = \frac{(C_{fi} - C_{pi})}{C_{fi}} \tag{5}$$

where C_{fi} is the feed concentration of the RO element i and C_{pi} is the permeate concentration of the RO element i.

As an approximation it can be considered:

$$\pi_{pi} = \pi_{fi}(1 - SR_i) \tag{6}$$

Replacing terms in (3):

$$Pnet_i = P_{fi} - \frac{\Delta P_{fri}}{2} - P_{pi} - \pi_{fi}[(RF_i \cdot CP_i) - (1 - SR_i)] \tag{7}$$

Eq. (1) refers to the entire RO system which will be:

$$Q = Qw_{mi} = Kw_{mi}(Pd_{mi} - \pi d_{mi})S_{mi} \tag{8}$$

Considering the average values by RO element, the above equation can be written as follows:

$$Q = N_e \cdot S_e \cdot \overline{K}_{Wm}(\pi_{fr}) \cdot \mathrm{TCF} \cdot F_t \cdot \left\{ P_f - \frac{\Delta P_{fr}}{2} - P_p - \pi_f\left[(RF \cdot \overline{CP}) - (1 - \overline{SR})\right] \right\} \tag{9}$$

where Q is total permeate flow (production capacity of the RO system), N_e are total RO elements of the RO system, S_e is membrane surface per RO element, $\overline{K}_{Wm}(\pi_{fr})$ is the average water permeability coefficient of the membrane m of the RO system (depending on the osmotic pressure of the feed-reject average concentration of the RO system) at 25°C, TCF is the temperature correction factor of the membrane m, F_t is the operating time factor, P_f is the feed pressure of the RO system, ΔP_{fr} is the feed-reject pressure drop of the RO system, P_p is the permeate pressure of the RO system, π_f is the osmotic pressure of the feed concentration of the RO system, RF is the recovery factor of the RO system, $\overline{CP}$ is the average value of the concentration polarization of the RO elements of the RO system, and $\overline{SR}$ is the average salt rejection of the RO system.

The above equation can be written as follows:

$$Q/[N_e \cdot S_e \cdot \overline{K}_{Wm}(\pi_{fr}) \cdot \mathrm{TCF} \cdot F_t] = P_f - \frac{\Delta P_{fr}}{2} - P_p - \pi_f\left[(RF \cdot \overline{CP}) - (1 - \overline{SR})\right] \tag{10}$$

From which we get the feed pressure:

$$P_f = Q/[N_e \cdot S_e \cdot \overline{K}_{Wm}(\pi_{fr}) \cdot \mathrm{TCF} \cdot F_t] + \frac{\Delta P_{fr}}{2} + P_p + \pi_f\left[(RF \cdot \overline{CP}) - (1 - \overline{SR}_s)\right] \tag{11}$$

According to the previous reasoning and considering the average values by RO element, Eq. (2) relative to the entire RO system can be written as follows:

$$Qj = Qj_{mi} = Kj_{mi} \cdot = Cdj_{mi} \cdot = S_{mi} \tag{12}$$

$$Qj = Kj_{mi} \cdot (Cj_{fri} - Cj_{pi}) \cdot S_{mi} \tag{13}$$

$$Qj = N_e \cdot S_e \cdot \overline{K}_{jm} \cdot \mathrm{TCF} \cdot (\overline{Cj}_{fr} - Cj_p) \tag{14}$$

where Qj is the entire flow of ion j across the membranes of the RO system, N_e are the entire RO elements of the RO system, S_e is membrane surface per RO element, $\overline{K}_{jm}$ is the average ion j permeability coefficient of the membrane m of the RO system at 25°C, TCF is the temperature correction factor of the membrane m, $\overline{Cj}_{fr}$ is the average feed-reject concentration of the ion j of the RO system, and Cj_p is the ion j concentration in the permeate of the RO system.

If it is considered that: $\overline{Cj}_{fr} - Cj_p \approx \overline{Cj}_{fr}$ and taking into account the RF (recovery factor of the RO system) and $\overline{CP}$ (average value of the concentration polarization per RO element of the RO system), Eq. (14) can be written as follows:

$$Qj = N_e \cdot S_e \cdot \overline{K}_{jm} \cdot \text{TCF} \cdot Cj_f \cdot RF \cdot \overline{CP} \tag{15}$$

In which Cj_f is the ion j concentration in the feed water of the RO system. Considering that:

$$Qj = Q \cdot Cj_p \tag{16}$$

From Eqs. (15) and (16) we get the product water concentration of the RO system (C_p):

$$Cj_p = \frac{N_e \cdot S_e \cdot \bar{K}_{jm} \cdot \text{TCF} \cdot Cj_f \cdot RF \cdot \overline{CP}}{Q} \tag{17}$$

$$C_p = Cj_p = \text{TDS}_p \tag{18}$$

where TDS_p is total dissolved salts in the product water.

3. Feed pressure calculation

From Eq. (11) and according to Fig. 2, we proceed to do the following calculations:

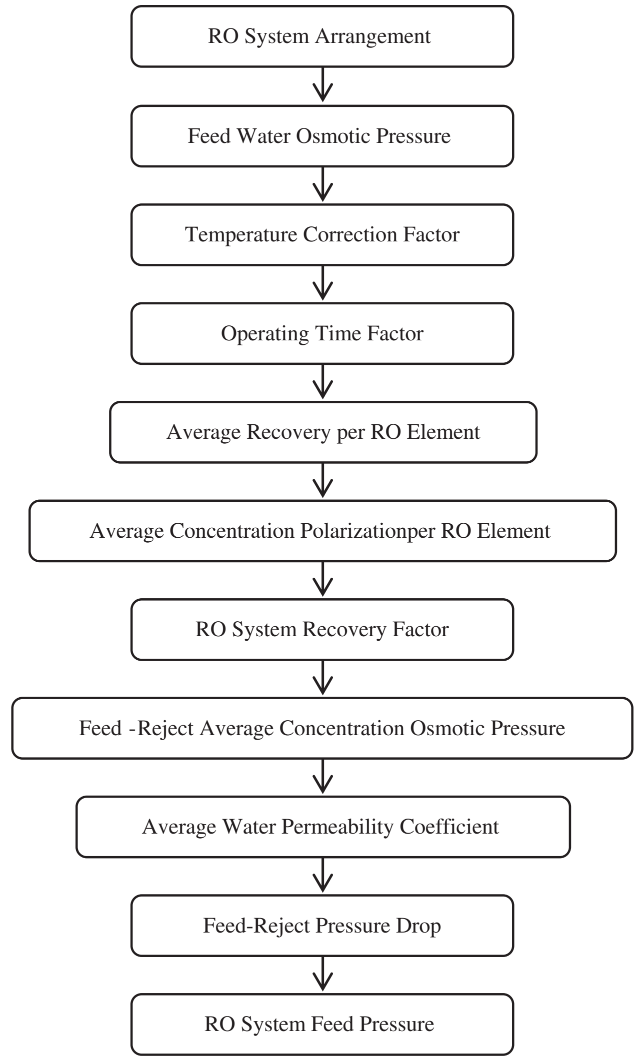

Fig. 2. Feed pressure calculation.

3.1. *Feed water osmotic pressure* (π_f)

Using the following equations [13]:

$$\pi_f = 0.076(T + 273.15)(m_i)_f(\text{atm}) \tag{19}$$

$$\pi_f = 0.0785(T + 273.15)(m_i)_f(\text{kg/cm}^2) \tag{20}$$

$$\pi_f = 1.1167(T + 273.15)(m_i)_f(\text{psi}) \tag{21}$$

where T is temperature (℃) and $(m_i)_f$ is molal concentration of the ion i in the feed water.

3.2. *Temperature correction factor*

Using the following equations [14]:

$$\text{For } T \leq 25^\circ\text{C} : \text{TCF} = e^{3{,}480\left\{\left(\frac{1}{298}\right) - \left[\frac{1}{(273+T)}\right]\right\}} \tag{22}$$

$$\text{For } T > 25^\circ\text{C} : \text{TCF} = e^{2{,}640\left\{\left(\frac{1}{298}\right) - \left[\frac{1}{(273+T)}\right]\right\}} \tag{23}$$

3.3. *Operating time factor* (F_t)

Using the following values [1,9]:

$$\text{For } t = 0 \text{ years} : F_t = F_0 = 1 \tag{24}$$

$$\text{For } t = 1 \text{ years} : F_t = F_1 = 0.9 \tag{25}$$

$$\text{For } t = 3 \text{ years} : F_t = F_3 = 0.8 \tag{26}$$

$$\text{For } t = 5 \text{ years} : F_t = F_5 = 0.7 \tag{27}$$

3.4. Average recovery per RO element ($\overline{R}_{\mathrm{i}}$)

Using the following equation [14]:

$$\overline{R}_{\mathrm{i}} = 1 - \left[1 - \left(\frac{R_{\mathrm{RO}}}{100}\right)\right]^{\frac{1}{n}} \tag{28}$$

where R_{RO} is the RO system recovery (%) and n is the following value:

- For one-stage RO systems ($R_{\mathrm{RO}} \leqslant 53$) [4]:

$$n = N_{\text{e-pv}} \tag{29}$$

- For two-stages RO systems ($53 < R_{\mathrm{RO}} \leqslant 87$) [4]:

$$n = 2N_{\text{e-pv}} \tag{30}$$

where $N_{\text{e-pv}}$ are total RO elements per pressure vessel of the RO system.

3.5. Average concentration polarization per RO element ($\overline{CP}$)

Using the following equation [14–16]:

$$\overline{PC} = e^{0.7\overline{R}_{\mathrm{i}}} \tag{31}$$

3.6. Recovery factor of the RO system (RF)

Using the following equation [13,14]:

$$RF = \frac{\ln \frac{100}{(100 - R_{\mathrm{RO}})}}{\left(\frac{R_{\mathrm{RO}}}{100}\right)} \tag{32}$$

3.7. Osmotic pressure of the average feed-reject concentration of the RO system (π_{fr})

Using the following equation [13,14]:

$$\pi_{\mathrm{fr}} = \pi_{\mathrm{f}} \cdot RF \cdot \overline{CP} \tag{33}$$

3.8. Average water permeability coefficients of the membrane m of the RO system at T °C [$\overline{K}_{Wm}$ (π_{fr}, T)]

Using the following equations [14]:

- For $\pi_{\mathrm{fr}} \leq 25\,\mathrm{psi}$:

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{gallons}}{(\text{ft}^2 \cdot \text{day} \cdot \text{psi})}\right] = 0.125 \cdot \text{TCF} \tag{34}$$

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{m}^3}{(\text{m}^2 \cdot \text{day} \cdot \text{kg/cm}^2)}\right] = 0.0724 \cdot \text{TCF} \tag{35}$$

- For $25 < \pi_{\mathrm{fr}} \leq 200\,\mathrm{psi}$:

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{gallons}}{(\text{ft}^2 \cdot \text{day} \cdot \text{psi})}\right] = 0.125 \cdot \text{TCF} - \left[\frac{0.011(\pi_{\mathrm{fr}} - 25)}{35}\right] \cdot \text{TCF} \tag{36}$$

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{m}^3}{(\text{m}^2 \cdot \text{day} \cdot \text{kg/cm}^2)}\right] = 0.5795 \cdot \overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{gallons}}{(\text{ft}^2 \cdot \text{day} \cdot \text{psi})}\right] \tag{37}$$

- For $200 < \pi_{\mathrm{fr}} \leq 400\,\mathrm{psi}$:

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{gallons}}{(\text{ft}^2 \cdot \text{day} \cdot \text{psi})}\right] = 0.125 \cdot \text{TCF} - [0.0001(\pi_{\mathrm{fr}} - 200)] \cdot \text{TCF} \tag{38}$$

$$\overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{m}^3}{(\text{m}^2 \cdot \text{day} \cdot \text{kg/cm}^2)}\right] = 0.5795 \cdot \overline{K}_{Wm}(\pi_{\mathrm{fr}}, T)\left[\frac{\text{gallons}}{(\text{ft}^2 \cdot \text{day} \cdot \text{psi})}\right] \tag{39}$$

3.9 Feed-reject pressure drop of the RO system (ΔP_{fr})

Using the following equations [10,14]:

- For one-stage RO systems ($R_{\mathrm{RO}} \leqslant 53$):
  - For 4´´X40´´ RO elements:

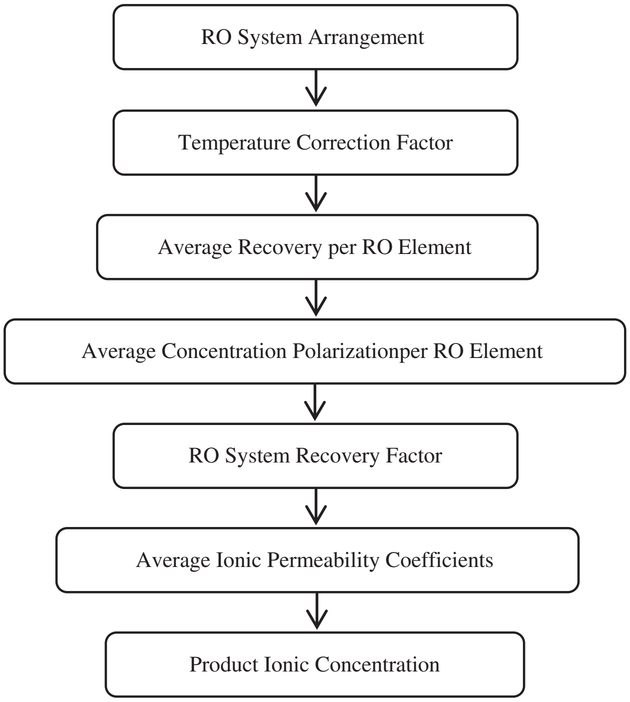

Fig. 3. Product water quality calculation.

$$\Delta P_{\text{fr}}(\text{psi}) = 0.1 \cdot N_{\text{e-pv}} \cdot (\overline{F}_{\text{fr-pv}})^{1.7} \tag{40}$$

$$\Delta P_{\text{fr}}\left(\frac{kg}{cm^2}\right) = 0.0703 \cdot \Delta P_{\text{fr}}(\text{psi}) \tag{41}$$

○ For 8´´X40´´ RO elements:

$$\Delta P_{\text{fr}}(\text{psi}) = 0.01 \cdot N_{\text{e-pv}} \cdot (\overline{F}_{\text{fr-pv}})^{1.7} \tag{42}$$

$$\Delta P_{\text{fr}}\left(\frac{kg}{cm^2}\right) = 0.0703 \cdot \Delta P_{\text{fr}}(\text{psi}) \tag{43}$$

where $\overline{F}_{\text{fr-pv}}$ is the arithmetic average value of the feed-reject flow per pressure vessel expressed in gallons per minute (GPM):

$$\overline{F}_{\text{fr-pv}} = \frac{F_{\text{f-pv}} + F_{\text{r-pv}}}{2} \tag{44}$$

where $F_{\text{f-pv}}$ is the feed flow per pressure vessel and $F_{\text{r-pv}}$ is the reject flow per pressure vessel.

- For two-stages RO systems ($53 < R_{\text{RO}} \leqslant 87$):

  ○ For 4´´X40´´ RO elements:

Table 1
Average ionic permeability coefficients at 25˚C

Ion	Salt rejection (%)	Salt pass. (%)	$\overline{K}_{\text{jm}}$ (m/day)
Ca^{2+}	99.30	0.70	0.00303
Mg^{2+}	99.44	0.56	0.00242
Na^{+}	97.30	2.70	0.01117
K^{+}	96.30	3.70	0.01600
HCO_3^{-}	98.61	1.39	0.00601
$SO_4^{=}$	99.93	0.07	0.00030
NO_3^{-}	90.34	9.66	0.04707
Cl^{-}	98.13	1.87	0.00809
SiO_2	99.41	0.59	0.00255

$$\Delta P_{\text{fr}}(\text{psi}) = 0.1 \cdot N_{\text{e-pv}} \cdot A(B + C) \tag{45}$$

$$\Delta P_{\text{fr}}\left(\frac{kg}{cm^2}\right) = 0.0703 \cdot \Delta P_{\text{fr}}(\text{psi}) \tag{46}$$

○ For 8´´X40´´ RO elements:

$$\Delta P_{\text{fr}}(\text{psi}) = 0.01 \cdot N_{\text{e-pv}} \cdot A(B + C) \tag{47}$$

$$\Delta P_{\text{fr}}\left(\frac{kg}{cm^2}\right) = 0.0703 \cdot \Delta P_{\text{fr}}(\text{psi}) \tag{48}$$

Equations in which the terms A, B, and C represent the following values:

$$A = \left(\frac{Q_{\text{p}}}{2R_{\text{RO}}}\right)^{1.7} \tag{49}$$

$$B = \left(\frac{100 + 8N_{\text{e}}\text{-pv}}{N_{\text{pv-1s}}}\right)^{1.7} \tag{50}$$

$$C = \left(\frac{13N_{\text{e-pv}}}{N_{pv-2s}}\right)^{1.7} \tag{51}$$

where Q_{p} is total permeate flow of the RO system expressed in GPM, $N_{\text{pv-1s}}$ is total pressure vessels of the first stage, and $N_{\text{pv-2s}}$ is total pressure vessels of the second stage.

3.10. Feed pressure of the RO system (P_{f})

Applying Eq. (11) at five cases indicated by Eqs. (24)–(27), we get different feed pressures over the

Table 2
Feed water chemical analysis

Sample	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	$SO_4^=$	NO_3^-	Cl^-	SiO_2	Fe	TDS	pH	T_{min}	T_{max}	SDI
1	96.10	139.70	958.27	32.30	668.70	695.20	382.50	963.00	35.00	0.10	3,970.77	7.80	22.0	22.0	2.70
2	681.50	489.10	413.34	26.30	74.30	573.50	115.10	2,760.50	22.50	0.10	5,156.14	6.90	22.0	24.0	2.50
3	58.60	89.10	2,920.43	45.20	475.30	1,063.40	21.50	3,832.20	25.20	0.10	8,530.93	7.70	24.0	26.0	2.60

first five years of operation of the reverse osmosis system. Considering the water temperature, we obtain:

- Minimum feed pressure ($P_{\text{f-min}}$) for $T = T_{\max}$ and $t = 0$ years.
- Average feed pressure ($P_{\text{f-med}}$) for $T = T_{\text{med}}$ and $t = 3$ years.
- Maximum feed pressure ($P_{\text{f-max}}$) for $T = T_{\min}$ and $t = 5$ years.

4. Product water quality calculation

From Eqs. (17)–(18) and according to Fig. 3, the following calculations are made in the previous section:

- *Temperature correction factor* (*TCF*): Eqs. (22) and (23).
- *Average recovery per RO element* ($\bar{R}_i$): Eqs. (28)–(30).
- *Average concentration polarization per RO element* ($\overline{CP}$): Eq. (31).
- *Recovery factor of the RO system* (*RF*): Eq. (32).

Considering the average ionic permeability coefficients of the membrane of the RO system relating to the temperature at 25˚C ($\overline{K}_{jm}$) is indicated in Table 1 [17].

Considering the water temperature, we obtain:

- Minimum product water concentration ($C_{\text{p-min}} = TDS_{\text{p-min}}$) for $T = T_{\min}$.
- Average product water concentration ($C_{\text{p-med}} = TDS_{\text{p-med}}$) for $T = T_{\text{med}}$.
- Maximum product water concentration ($C_{\text{p-max}} = TDS_{\text{p-max}}$) for $T = T_{\max}$.

We can estimate the values of pH of the above product water concentrations (pH_p), using the equation [2–4]:

$$\text{pH}_p = 6.3 + \log\left\{\frac{[\text{HCO}_3]_p}{(\text{CO}_2)_p}\right\} = 6.3 + \log\left\{\frac{[\text{HCO}_3]_p}{(\text{CO}_2)_f}\right\} \tag{52}$$

where $[HCO_3]_p$ (product water bicarbonates concentration) is expressed in ppm as $CaCO_3$, $(CO_2)_p$ is product water carbon dioxide concentration expressed in mg/l, and considering that $(CO_2)_p = (CO_2)_f$ (feed water carbon dioxide concentration).

5. Practical application

Three samples of brackish water from wells in the Canary Islands were used for this study. The samples were taken from feed water of RO desalination plants. The chemical analyses are shown in Table 2 (concentrations in mg/l as ion and temperatures in ℃) [10]. The capacities of these BWRO desalination plants are 600 (sample 1), 500 (sample 2), and 300 m^3/day (sample 3).

The possible RO system arrangements for 4´´ and 8´´ RO elements are shown in Table 3 [10].

6. Results

From the RO system arrangements (Table 3), the feed pressure and the product water quality of the RO systems are calculated. The calculations were computed with MATLAB R2008a. The results for 8´´X40´´ RO elements are shown in Table 4.

The Table 5 shows a comparison between the results obtained in simulation 2, using the proposed method and using the manufacturer's software membrane, with the actual values after three years of plant operation.

Table 3
RO system arrangements

RO system	1	2	3
Capacity (m^3/day)	600	500	300
TDS_f (mg/l)	3,970.77	5,156.14	8,530.93
$R_{max\text{-}adopt}$ (%)	67.47	74.43	79.45
$(TDS)_r$ for $R_{max\text{-}adopt}$	12,206	20,166	41,506
R_{RO} (%)	67	71	52
$N_{e\text{-}pv}$	6	6	6
Stages	2	2	1
$N_{pv\text{-}4}$ (A0)	0	0	10
$N_{pv\text{-}8}$ (A0)	0	0	3
$N_{pv\text{-}4}$ (A1)	24	21	0
$N_{pv\text{-}4}$ (A2)	25	20	0
$N_{pv\text{-}8}$ (A1)	6	0	0
$N_{pv\text{-}8}$ (A2)	0	5	0
4´´ arrangement (A1)	16 + 8	14 + 7	0
4´´ arrangement (A2)	15 + 10	12 + 8	0
8´´ arrangement (A1)	4 + 2	0	0
8´´ arrangement (A2)	0	3 + 2	0
$N_{e\text{-}4}$ (A0)	0	0	60
$N_{e\text{-}8}$ (A0)	0	0	18
$N_{e\text{-}4}$ (A1)	144	126	0
$N_{e\text{-}4}$ (A2)	150	120	0
$N_{e\text{-}8}$ (A1)	36	0	0
$N_{e\text{-}8}$ (A2)	0	30	0

Table 4
Feed pressure and product water quality

Simulation	1	2	3
Capacity (m^3/day)	600	500	300
RO element (ØXL)	8´´X40´´	8´´X40´´	8´´X40´´
S_e (m^2)	37	37	37
$P_{f\text{-}med}$ (A0) (kg/cm^2)	0.00	0.00	20.96
$P_{f\text{-}med}$ (A1) (kg/cm^2)	15.58	0.00	0.00
$P_{f\text{-}med}$ (A2) (kg/cm^2)	0.00	17.83	0.00
$P_{f\text{-}max}$ (A0) (kg/cm^2)	0.00	0.00	22.92
$P_{f\text{-}max}$ (A1) (kg/cm^2)	16.95	0.00	0.00
$P_{f\text{-}max}$ (A2) (kg/cm^2)	0.00	19.70	0.00
$TDS_{p\text{-}med}$ (A0) (mg/l)	0.00	0.00	234.33
$pH_{p\text{-}med}$ (A0)	0.00	0.00	6.01
$TDS_{p\text{-}med}$ (A1) (mg/l)	145.61	0.00	0.00
$pH_{p\text{-}med}$ (A1)	6.12	0.00	0.00
$TDS_{p\text{-}med}$ (A2) (mg/l)	0.00	140.64	0.00
$pH_{p\text{-}med}$ (A2)	0.00	5.26	0.00
$TDS_{p\text{-}max}$ (A0) (mg/l)	0.00	0.00	241.38
$pH_{p\text{-}max}$ (A0)	0.00	0.00	6.02
$TDS_{p\text{-}max}$ (A1) (mg/l)	145.61	0.00	0.00
$pH_{p\text{-}max}$ (A1)	6.12	0.00	0.00
$TDS_{p\text{-}max}$ (A2) (mg/l)	0.00	146.32	0.00
$pH_{p\text{-}max}$ (A2)	0.00	5.28	0.00

Table 5
Results comparison

Simulation 2	Real	Simulation	Filmtec
Capacity (m^3/day)	500	500	500
Production (m^3/h)	21.00	20.83	20.83
Recovery (%)	67.74	71.00	71.00
RO element (ØXL)	8´´X40´´	8´´X40´´	8´´X40´´
S_e (m^2)	37	37	37
8´´ arrangement (A2)	3 + 2	3 + 2	3 + 2
Temperature (℃)	23	23	23
TDS_f (mg/l)	5,082.24	5,156.14	5,142.90
Operating time (h)	25,016	24,000	24,000
P_f (kg/cm^2)	19.00	17.83	15.63
TDS_p (mg/l)	133.40	140.64	103.48

7. Conclusions

From the obtained results (Tables 4 and 5), the following conclusions can be assumed:

- Validity of the proposed design method.
- It is easy to use and has a high degree of confidence.
- Keeping the arrangement it is possible to change the RO elements (4´´X40´´ and 8´´X40´´) in order to improve the desalination plant performance.

The RO system design of a brackish water desalination plant employing this procedure, will need to consider, in addition to the results previously described, other limiting factors including economics, the type of RO element to be employed, the maximum operating pressure, the desired product water quality, etc.

The proposed method enables the use of a simple calculation software program which can be integrated into the definitive calculation program used for the BWRO plant design. In this way, later simulations can be easily applied with a high degree of confidence.

The RO system has been designed with the less active membrane area of 4´´x40´´ and 8´´x40´´ elements. These elements can be changed for larger active area of 4´´X40´´ and 8´´X40´´ elements, e.g. BW30LP-4040 ($S_{E\text{-}4} = 7.25\,m^2$) and BW30-365 ($S_{E\text{-}8} = 34\,m^2$) and BW30-400 ($S_{E\text{-}8} = 37\,m^2$) and BW30-440 ($S_{E\text{-}8} = 41\,m^2$) Filmtec elements [1] keeping the same RO system arrangement, in order to reduce the operating pressure of the plant.

Symbols

A ( )	—	Arrangement
A (0)	—	One-stage arrangement
A (1)	—	Two-stage arrangement (2:1)
A (2)	—	Two-stage arrangement (3:2)
BW, bw	—	Brackish water
C_{fi}	—	Feed concentration of the RO element i
C_{pi}	—	Product concentration of the RO element i
Cdj_{mi}	—	Differential ion j concentration across the membrane of the RO element i
Cds_{mi}	—	Differential salt concentration across the membrane of the RO element i
Cj_f	—	Ion j concentration in the feed water of the RO system
Cj_p	—	Ion j concentration in the permeate of the RO system
$\overline{Cj}_{fr}$	—	Average feed-reject concentration of the ion j of RO system
Cj_{fri}	—	Average feed-reject concentration of the ion j of RO element i
C_p	—	Product water concentration of the RO system
$C_{p\text{-}max}$	—	Maximum product water concentration of the RO system
$C_{p\text{-}med}$	—	Medium product water concentration of the RO system
$C_{p\text{-}min}$	—	Minimum product water concentration of the RO system
$\overline{CP}$	—	Average concentration polarization per RO element of the RO system
CP_i	—	Concentration polarization in the RO element i
F_t	—	Operating time factor
$F_{f\text{-}pv}$	—	Feed flow per pressure vessel
$F_{r\text{-}pv}$	—	Reject flow per pressure vessel
FT30	—	Filmtec spiral wound membrane
L	—	Length
$\overline{K}_{jm}$	—	Average ion j permeability coefficient of the membrane of the RO system at 25°C
Kj_{mi}	—	Ion j permeability coefficient of the membrane of the RO element i
Kw_{mi}	—	Water permeability coefficient of the membrane of the RO element i
$\overline{K}_{Wm}(T)$	—	Average water permeability coefficient of the membrane of the RO system at T (°C)
$\overline{K}_{Wm}(\pi_{fr})$	—	Average water permeability coefficient of the membrane of the RO system at 25°C
Ks_{mi}	—	Salt permeability coefficient of the membrane of the RO element i
LSI	—	Langelier saturation index
$(m_i)_f$	—	Molal concentration of the ion i in the feed water
N_e	—	Total RO elements of the RO system
$N_{e\text{-}4}$	—	Total 4´´ RO elements
$N_{e\text{-}8}$	—	Total 8´´ RO elements
$N_{e\text{-}pv}$	—	Total RO elements per pressure vessel
$N_{e\text{-}pv\text{-}4}$	—	Total 4´´ RO elements per pressure vessel
$N_{e\text{-}pv\text{-}8}$	—	Total 8´´ RO elements per pressure vessel
$N_{pv\text{-}4}$	—	Total 4´´ pressure vessels
$N_{pv\text{-}8}$	—	Total 8´´ pressure vessels
$N_{pv\text{-}1s}$	—	Total pressure vessels of the first stage
$N_{pv\text{-}2s}$	—	Total pressure vessels of the second stage
$N_{pv\text{-}4\text{-}1s}$	—	Total first stage 4´´ pressure vessels
$N_{pv\text{-}8\text{-}1s}$	—	Total first stage 8´´ pressure vessels
$N_{pv\text{-}4\text{-}2s}$	—	Total second stage 4´´ pressure vessels
$N_{pv\text{-}8\text{-}2s}$	—	Total second stage 8´´ pressure vessels
Pd_{mi}	—	Differential pressure across the membrane of the RO element i
P_f	—	Feed pressure of the RO system
$P_{f\text{-}max}$	—	Maximum feed pressure of the RO system
$P_{f\text{-}med}$	—	Medium feed pressure of the RO system
$P_{f\text{-}min}$	—	Minimum feed pressure of the RO system
P_{fi}	—	Feed pressure of the RO element i
pH	—	Water pH value
pH_p	—	Product water pH value
$Pnet_i$	—	Net or effective pressure on the RO element i
P_p	—	Permeate pressure of the RO system
P_{pi}	—	Permeate pressure of the RO element i
PV, pv	—	Pressure vessel
Q	—	Production capacity

Qj	—	Total ion j flow across the membranes of the RO system
Q_p	—	Total permeate flow of the RO system
Qj_{mi}	—	Total ion j flow across the membranes of the RO element *i* of the RO system
Qs_{mi}	—	Salt flow through the RO element i
Qw_{mi}	—	Permeate flow through the RO element i
$R_{max\text{-}adopt}$	—	Maximum recovery adopted
R_{RO}	—	RO system recovery (%)
$R_{RO\text{-}4}$	—	4´´ RO system recovery (%)
$R_{RO\text{-}8}$	—	8´´ RO system recovery (%)
RF	—	Recovery factor of the RO system
RF_i	—	Recovery factor of the RO element i
$\overline{R}_i$	—	Average recovery per RO element
RO, ro	—	Reverse osmosis
SDI	—	Silt density index
S_e	—	Membrane surface per RO element
$S_{e\text{-}4}$	—	Membrane surface per 4´´ RO element
$S_{e\text{-}8}$	—	Membrane surface per 8´´ RO element
$\overline{SR}$	—	Average salt rejection of the RO system
SR_i	—	Salt rejection of the RO element i
S_{mi}	—	Membrane surface of the RO element i
T	—	Feed water temperature (℃)
T_{max}	—	Maximum feed water temperature (℃)
T_{med}	—	Medium feed water temperature (℃)
T_{min}	—	Minimum feed water temperature (℃)
TCF	—	Temperature correction factor
TDS	—	Total dissolved salts
TDS_f	—	Total dissolved salts in the feed water
TDS_p	—	Total dissolved salts in the product water
$TDS_{p\text{-}max}$	—	Maximum total dissolved salts in the product water
$TDS_{p\text{-}med}$	—	Medium total dissolved salts in the product water
$TDS_{p\text{-}min}$	—	Minimum total dissolved salts in the product water
TDS_r	—	Total dissolved salts in the reject water
Ø	—	Diameter
ΔP_{fr}	—	Feed-reject pressure drop of the RO system
$\Delta P_{fr}(\text{psi})$	—	Feed-reject pressure drop of the RO system expressed in psi
$\Delta P_{fr}\left(\frac{kg}{cm^2}\right)$	—	Feed-reject pressure drop of the RO system expressed in $\left(\frac{kg}{cm^2}\right)$
ΔP_{fri}	—	Feed-reject pressure drop of the RO element i
πd_{mi}	—	Differential osmotic pressure across the membrane of the RO element i
π_f	—	Osmotic pressure of the feed concentration of the RO system
π_{fi}	—	Osmotic pressure of the feed concentration of the RO element i
π_{fr}	—	Osmotic pressure of the average feed-reject concentration of the RO system
π_{fri}	—	Osmotic pressure of the feed-reject average concentration of the RO element i
π_{pi}	—	Osmotic pressure of the permeate concentration of the RO element i

Subscripts

e	—	Element
f	—	Feed
p	—	Product, permeate
r	—	Reject
t	—	Time

References

[1] Dow Chemical Co., Filmtec Membranes, BW30 RO Elements.

[2] Instituto Geológico y Minero de España (IGME), Isotopos Ambientales en el Ciclo Hidrológico. Principios y Aplicaciones, Capítulo 9: Química del Ácido Carbónico del Agua [Environmental isotopes in the hydrological cicle. Principles and Applications IHP-V Technical Documents in Hydrology, no. 39], Programa Hidrológico Internacional, UNESCO-IAEA, 2001, pp. 101–107.

[3] American Society for Testing and Materials (ASTM), Standard Practice for Calculation and Adjustment of the Langelier Saturation Index for Reverse Osmosis, Annual Book, Designation: D 3739-88, 1988.

[4] American Society for Testing and Materials (ASTM), Standard Practice for Calculation and Adjustment of the Stiff and Davis Stability Index for Reverse Osmosis, Annual Book, Designation: D 4582-86, 1986.

[5] American Society for Testing and Materials (ASTM), Standard Practice for Calculation and Adjustment of Sulphate Scaling Salts ($CaSO_4$, $SrSO_4$, and $BaSO_4$) for Reverse Osmosis, Annual Book, Designation: D 4692-87, 1987.

[6] G.B. Alexander, W.M. Hester, R.K. ller, The solubility of amorphous silica in water, J. Phys. Chem. 58 (1954) 453–455.

[7] American Society for Testing and Materials (ASTM), Standard Practice for Calculation and Adjustment of Silica (SiO_2) Scaling for Reverse Osmosis, Annual Book, Designation: D 4993-89, 1989.

[8] M. Al-Shammiri, A. Salman, S. Al-Shammari, M. Ahmad, Simple program for the estimation of scaling potential in RO systems, Desalination 184 (2005) 139–147.

[9] E.R. Saavedra, A.G. Gotor, S.O. Pérez Báez, A.R. Martín, Estimation of the maximum conversion level in reverse osmosis brackish water desalination plants, Desalin. Water Treat. 51 (2013) 1143–1150.

[10] E.R. Saavedra, A.G. Gotor, S.O. Pérez Báez, A.R. Martín, A. Ruiz-García, A.C. González, A design method of the RO system in reverse osmosis brackish water desalination plants (procedure), Desalin. Water Treat. 51 (2013) 4790–4799.
[11] U. Merten, H.K. Lonsdale, R.L. Riley, Boundary-layer effects in reverse osmosis, Ind. Eng. Chem. Fundam. 3 (1964) 210–213.
[12] H.K. Lonsdale, U. Merten, R.L. Riley, Transport properties of cellulose acetate osmotic membranes. J. Appl. Polym. Sci. 9(4) (1965) 1341–1362.
[13] American Society for Testing and Materials (ASTM), Standard Practice for Standardizing Reverse Osmosis Performance Data, Annual Book, Designation: D 4516-85, 1985.
[14] Dow Chemical Co., Filmtec Co., Filmtec Membranes Technical Manual, Section 4: System Design, 1995.
[15] Gulf Environmental Systems Co., Reverse Osmosis Principles and Applications, Report 10023, 37, 1974.
[16] Office of Water Research and Technology, U. S. Department of the Interior, Reverse Osmosis Technical Manual, OWRT TT/80 2, 1979.
[17] E.R. Saavedra, A.G. Gotor, S.O. Pérez Báez, A.R. Martín, A. Ruiz-García, A.C. González, Evaluation of the five years operating data of a RO brackish water desalination plant in Las Palmas, Canary Islands, Spain: A historic case, Desalin. Water Treat. 51 (2013) 4785–4789.