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Backwashing pressurized ultrafiltration using reverse osmosis brine in seawater desalination and its potential costs savings

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ABSTRACT

This paper discusses the feasibility of using reverse osmosis concentrate to backwash ultrafiltration membranes in the seawater reverse osmosis desalination space. Brine is produced through DOW FILMTEC™ reverse osmosis elements and it backwashed every 90 min to DOW™ ultrafiltration membranes. A side-by-side validation is done for 15 d using two parallel ultrafiltration and reverse osmosis integrated systems. One line uses brine for backwashing, while the other uses conventional filtrated water. The optimization is proven to have the same cleaning efficiency than the conventional backwashing methods and no precipitation is observed in the fibers. An additional validation period that uses reverse osmosis brine during backwashes and only two backwash steps is also carried out successfully. These steps are the previously identified backwash top with air scour and forward flush. Fibers also show an excellent integrity after the whole experimental period. A model is built in order to analyze the backwash efficiency of the optimized conditions and the transmembrane pressure increases during the filtration cycle. The results show the same fouling tendency for the line operating with brine and the line operating with filtrated water. The efficiency of the ultrafiltration process is improved from 88 to 98% thanks to this optimization together with the previous researches. This represents filtrating 96 min extra per day and a reduction of 100% in the filtrated water used during backwashes. The chemical equivalent concentration is also optimized from 0.28 to 0.06 mg/L NaClO thanks to the adjustment of the chemically enhanced backwash frequency. This accounts for a 7.1% savings in the ultrafiltration step and for a 1.2% savings in the whole desalination process.

Keywords: Ultrafiltration; Backwash; Efficiency; Brine; Cost; Fouling; Cleaning; Seawater; Desalination

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1. Introduction

The use of pressurized ultrafiltration as a pretreatment for the reverse osmosis membranes in seawater desalination has experimented an impressive increase as a result of the continuous search for cost-effective technologies which enable a sustainable production of water [1]. Key benefits associated with the ultrafiltration technology versus conventional pretreatment are a low footprint, the ability to remove virus and bacteria, and to significantly reduce colloids, suspended particles, turbidity (TB), and some total organic carbon (TOC). Even more importantly, the ability to reliably provide good quality filtrate water to the downstream reverse osmosis is the most remarkable benefit associated with this technology [2].

1.1. Ultrafiltration cleanings

The ultrafiltration process is characterized, unlike reverse osmosis, by having relatively short filtration cycles given the need for higher cleaning frequency. The duration of the filtration cycle strongly depends on the type of raw water leading to a filtration cycle between 10 and 100 min. Between two filtration cycles, a backwash (BW) will occur to enable the cleaning of the fibers and consequently, a reduction in the transmembrane pressure (TMP) accumulated during the filtration. A second type of cleaning, which takes place with a lower frequency compared with the backwash, is the chemically enhanced backwash (CEB). Often, the CEB occurs once or twice per day and is characterized by a longer duration compared with the backwash and also by the use of chemicals. The last type of cleanings, the cleaning in place (CIP) occurs once every couple of months and is characterized by its longer duration (few hours typically) and higher chemical concentrations used compared with a CEB.

Short-term cleanings such as the backwash are typically carried out every 10–80 min, with a median of 30 min. The median duration of all steps in the sequence is approximately 3 min, where the backwash takes about 1 min. The backwash flux varies between 70 and 300 L/mh (10/90% percentiles) and typically reflects double the operating flux. Occasionally, chemicals such as hydrogen peroxide (H_2O_2) and Sodium Metabisulfite are used as backwash chemicals, but were judged as less effective than chlorine, which is frequently used. As an example, backwash chemistry is evaluated comparing 25 mg/L H_2O_2 and 10 mg/L NaClO, and the NaClO chemistry seems to be far more effective [3]. NaClO has recently been the most widely used and has emerged as the standard for backwash schemes with chemicals. Its typical range is 3–20 mg/L with a median of 10 mg/L. Occasionally, especially in outside-in modules, air scouring is used in the range of 3–20 Nm/h for every 1–8 backwash cycles. The steps typically included in the backwash sequence are the Air Scour, with a duration between 30 and 60 s; the Draining, with a duration between 10 and 30 s; the Backwash Top with or without Air Scour, with a duration between 30 and 40 s; the Backwash Bottom, with a duration between 30 and 40 s; and the Forward Flush, with a duration between 10 and 60 s [4].

There are two types of CEB-type operations used for medium-term cleanings: an oxidizing CEB and an acidic CEB. The predominant oxidizing agent in CEB operations is NaClO at 20–500 mg/L (10 and 90% percentile), with a median of 150 mg/L. Lower concentrations in the 50 mg/L range are used more frequently in every 2–8 h [5], while higher concentrations are applied less frequently with a range of 12 and more hours. NaOH was tried in few occasions with and without NaClO but was quickly dismissed due to its scaling nature [6]. In fact, precipitations have already been discovered with NaClO, which is also a weak base [2]. In the acid CEB, most frequently, H_2SO_4 and HCl are used and also occasionally, citric acid is used. The frequency of the chlorine CEB is in the range of every 6 to every 92 h (10 and 90% percentile) with a median of 24 h. Acid CEB is carried out at a frequency of 1:1–1:3 compared with chlorine CEBs. The chemical dosing duration in CEB steps is typically 30 s, hence, shorter than the BW duration in a normal backwash. Information about CEB flux is very scarce—and as a rule of thumb, it is safe to assume that the CEB flux is equivalent to the backwash flux. In order to extend the chemical exposure duration, often extended soak times are provided after the chemical dosing—these are in the range of 2–36 min (10 and 90% percentile) and the median is 15 min.

Medium-term cleanings (which in the framework of this work are termed “CEB”) are the most diverse among all cleaning conditions and many different variations are described. A protocol that combined chemical dosing for only a very short-time period with air bubbling has also been proposed [7]. With outside-in technology, it has also been frequently described to automatically dose chemicals to the feed, instead of the product, and recirculate [8]. Finally, the addition of chemicals to reverse osmosis permeate is described as well. A special backwash protocol, involving the use of heated cleaning solution, not only in the CIP but also in the CEB is proposed as well [9,10]. This advanced method has also been described for medium-term cleanings, called “HEFM—Heated Enhanced Flux Maintenance”: at the Buzzer platform and the Brownsville pilot, “this method is used daily—each MF rack is taken offline and heated chlorine solution (at about 250–400 mg/L chlorine at 30–35°C) is automatically circulated through the MF membrane rack for about 30 min" [10,11]. Some CEB-type medium-term cleanings may carry character of a CIP operation, e.g. involving multiple hours soak duration and higher concentration.

Clean in place operations are carried out every 21 d to every 14 months, with a median of every 1.5 months. CIP operations are often composed of two steps: one which nowadays often uses NaClO at elevated concentrations (up to 4,000 mg/L with PVDF fibers) and optional NaOH (often pH~12); and a second one with acid (often organic acid at very high concentrations in the low percent range). Often, multiple hours of recirculation and soak time are used. Often heating is used to enhance the effect. A wide variety of special chemicals is reported, e.g. formulated cleaners, EDTA, or enzymes [12].

1.2. Advanced cleaning research

In the past, and in the seawater desalination space, DOW™ ultrafiltration membranes were used in Qingdao 2009 with an efficiency of 80% as some other commercially available ultrafiltration systems show nowadays. After the first improvement phase done in Barcelona, the efficiency of DOW™ ultrafiltration was increased to 88% [12].

Previous investigations have focused in reducing the number of backwash steps, so that the steps that contribute the less can be omitted. This reduction from five steps (Air Scour, Draining, Backwash Top with Air Scour, Backwash Bottom, and Forward Flush) to two steps (Backwash Top with Air Scour and Forward Flush) at a constant backwash frequency of 30 min increased the efficiency to 95%. This investigation was done by planning a fractional design of experiments and then by analyzing the TMP as a response variable throughout an analysis of variance [4].

Simultaneously, previous investigations focused on reducing the backwash frequency in order to raise the ultrafiltration efficiency to 96%. The experiments were done by keeping the five main backwash steps but reducing the backwash frequency from 30 to 90 min. Therefore, it was possible to operate the ultrafiltration system doing fewer backwashes per day [13].

The next investigation focused on keeping a low backwash frequency of 90 min, while reducing the number of backwash steps to two. This leaded to an efficiency increase of 97% [14].

The aim of this research is to prove the feasibility of doing backwashes using reverse osmosis concentrate. These improvements allow operating the ultrafiltration membranes at 98% efficiency.

1.3. Backwash using brine in desalination

The novelty of this research is highlighted because it gives real operating data in the desalination space. As an example of previous state of the art, older disclosures also suggested using reverse osmosis brine to clean the upstream pretreatment filters [15]. Some previous art also pointed a method linked to a specific designed product to collect reverse osmosis concentrate into a CIP tank, which is later used to backwash microfiltration membranes. However, this technology is linked a specific product. It is also not directly related to the desalination space. In addition, it is not related to ultrafiltration pore size but to microfiltration. Moreover, no real operating data are provided [16]. Other literature discloses a particular method related to a specific product to use reverse osmosis concentrate to backwash the microfiltration or ultrafiltration in the seawater desalination space. However, it claims that the brine must be previously treated before being used during the backwashes. Moreover, this literature lacks operating data that demonstrate its feasibility and its application, which is restricted to a very specific process [17].

2. Materials and methods

2.1. Unit description

This research is done in an experimental containerized seawater desalination plant. This unit represents one of the 20 experimental units that Dow Water & Process Solutions has in its Global Water Technology Development Center in Tarragona, Spain. Fig. 1 shows the scheme of the installation, which consists of two independent and parallel lines, both containing ultrafiltration membranes pretreatment to the reverse osmosis train. The pretreatment before the ultrafiltration unit includes an Amiad Arkal disk filter of 250 μm. The ultrafiltration modules used are DOW™ Ultrafiltration SFP-2660 modules, and DOW FILMTEC™ SW30XLE-4040 membranes are used for the reverse osmosis. This research is carried out using a brine tank to store reverse osmosis concentrate coming from both reverse osmosis lines. Brine tank is used for backwashing the first ultrafiltration line using brine. The backwash tank of the second ultrafiltration line is used to backwash the ultrafiltration unit of the second line.

2.2. Seawater characterization

Seawater from Mediterranean Sea and taken from Tarragona Harbor is used in this research. Water has a total dissolved solids salt content of 39,252 mg/L.

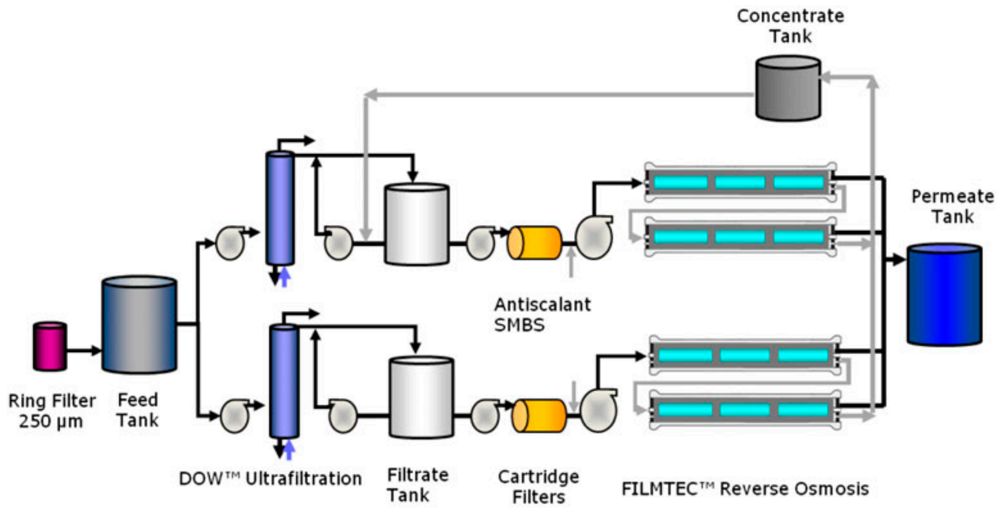

Fig. 1. Ultrafiltration and seawater reverse osmosis desalination plant.

Table 1 depicts the total ionic seawater characterization. TOC has an average value of 0.79 mg/L, Total suspended solids have an average value of 2.10 mg/L, and TB has an average value of 1.05 NTU. This analysis is done in the water analytical laboratory that Dow Water & Process Solutions has in Water Technology Application Development Global Center.

2.3. Normalization equations

The normalized (TMP^*) is calculated by multiplying the measured TMP by the temperature correction factor (TCF) as described by Eq. (1).

$$TMP^* = TCF \cdot TMP \tag{1}$$

Table 1
Seawater ion characterization

Ions	Concentration (mg/L)
Potassium (K)	446
Sodium (Na)	11,941
Magnesium (Mg)	1,483
Calcium (Ca)	465
Strontium (Sr)	10
Carbonate (CO_3)	4
Bicarbonate (HCO_3)	138
Chloride (Cl)	21,640
Fluoride (F)	1
Sulfate (SO_4)	3,045
Boron (B)	5
Bromide (Br)	74

The purpose of the TCF is to take into consideration the effect of the Temperature (T) in Celsius degrees and its influence on the viscosity of water, as described by Eq. (2) [18]. Therefore, different TMP values obtained at different temperatures can be compared and transported to the same reference temperature of 25˚C.

$$TCF = \frac{10^{\left(\frac{247.8}{25+273.16-140}\right)}}{10^{\left(\frac{247.8}{T+273.16-140}\right)}} \tag{2}$$

2.4. Efficiency assessment

Efficiency is defined as the net yield of the ultrafiltration process. It is obtained by multiplying the product water recovery yield by the availability yield. Efficiency is used to make a fair comparison between these two parameters, making sure both time and water produced are taken into consideration to calculate the overall process yield. This yield is calculated using Eq. (3).

$$\text{Efficiency} = \text{Availability} \cdot \text{Recovery} \tag{3}$$

Availability measures the time the ultrafiltration module is producing water. Therefore, the time when the unit is not filtrating is discounted. This yield is calculated using Eq. (4).

$$\text{Availability} = \frac{t_{\text{filtrating}}}{t_{\text{total}}} \tag{4}$$

Water product recovery measures net water produced. Filtrated water consumed during backwashes and CEBs is discounted. This yield is calculated using Equation 11.

$$\text{Recovery} = \frac{V_{\text{water produced}} - V_{\text{CEB}} - V_{\text{BW}}}{V_{\text{water produced}}} \quad (5)$$

Chemical equivalent concentration (CEC) represents the concentration of pure chemicals per volume of feed water if the system was operated continuously. It is calculated by dividing the total amount of pure chemicals between the water fed into an ultrafiltration system for a certain amount of time. This concentration is calculated using Eq. (6).

$$\text{CEC} = \frac{M_{\text{chemicals}}}{V_{\text{water fed}}} \quad (6)$$

2.5. Cost assessment

The cost assessment is carried out using the cost model published by Busch [12]. The cost is assessed for a seawater desalination plant with a nominal capacity of 75,000 m/d with a recovery rate of 47.5%.

2.6. Validation

The hypothesis of this research is that backwashes can be done using reverse osmosis concentrate, keeping the same backwash cleaning power.

Both ultrafiltration lines are operated for seven days at the same conditions as described in Table 2, but only using filtrated water during backwashes. This trial is done in order to discard any effect not related to the brine hypothesis validation. This will discard any effect due to the line itself or each membrane.

To validate this hypothesis, DOW™ ultrafiltration membranes are used for a two-week side-by-side experiment during 31 October 2012 and 15 November 2012. This trial consists of operating the first ultrafiltration line using reverse osmosis brine during backwashes. In parallel, the second ultrafiltration line uses filtrated water during backwashes. The TMP evolution over time is thus compared in both lines to assess any adverse influence of the first line using brine during backwashes. CEBs are performed only when the TMP is high and are thus needed in order to maximize the efficiency of the process. They are done using filtrated water to avoid any risk of calcium carbonates or magnesium hydroxide precipitating on the ultrafiltration fibers. The operating conditions of this first operating period for both lines are summarized in Table 2.

Finally, in order to combine all the ultrafiltration cleaning research work done in this thesis, a second validation period is performed from 25 January 2013 to 5 February 2013. Table 3 summarizes the operating conditions. Baseline operation reflects previous operation using filtrated water during backwashes and optimized cleaning steps. The other line uses reverse osmosis brine during backwashes and also uses the two most relevant cleaning steps identified in [4] and [14]. Both lines use a backwash frequency of 90 min as identified in [13].

Both reverse osmosis lines are operated at the conditions described in Table 4, so that the first ultrafiltration line has brine available to perform the backwashes. Both lines use Nalco PermaTreat PC-1020T to prevent scaling and sodium meatabisulfite to prevent membrane oxidation.

2.7. TMP modeling

The TMP evolution over time is modeled to predict the fouling trend in the long-term operation. This is achieved by analyzing the TMP at the starting and ending of each filtration cycle, each backwash cycle, and each CEB cycle. These three cases are: the TMP increase during filtration, the TMP reduction during backwash, and the TMP reduction during CEB. These three data-sets allow in obtaining of three different mathematical functions. These are used to predict the TMP increase over time. Analyzing the mathematically obtained coefficients, it is possible to assess the effectiveness of each cleaning. The ultimate goal of the modeling is to build a robust set of equations that enable the prediction of the long-term TMP evolution. Thanks to the model, the operator will be able to decide which operating conditions are more adequate to its installation depending on each type of cost, such as the cost of chemicals, the cost of electricity, and the cost of manpower.

2.8. Fiber Integrity

Pressure decay tests are done after each validation period to check the fibers integrity using the method described in [19].

3. Results and discussion

3.1. Validation

Fig. 2 shows the validation of both lines operated at the same conditions. No major differences between both ultrafiltration lines and modules are seen,

Table 2
Ultrafiltration baseline and optimum conditions of first validation period

Parameter	Baseline	Optimum
Flux	70 l/m^{2}h	70 l/m^{2}h
Backwash water type	Filtrate	Brine
Backwash frequency	90 min	90 min
Backwash flux	80 l/m^{2}h	80 l/m^{2}h
Air flow	5 Nm^3/h	5 Nm^3/h
Air Scour duration	30 s	30 s
Draining duration	30 s	30 s
Backwash top with air scour duration	30 s	30 s
Backwash bottom duration	30 s	30 s
Forward flush duration	30 s	30 s
Valve changing time	2 s	2 s
CEB water type	Filtrate	Filtrate
CEB frequency	When needed	When needed
NaClO concentration	350 mg/L	350 mg/L
Soaking time	6 min	6 min

Table 3
Ultrafiltration baseline and optimum conditions of second validation period

Parameter	Baseline	Brine
Flux	70 l/m^{2}h	70 l/m^{2}h
Backwash water type	Filtrate	Brine
Backwash frequency	90 min	90 min
Backwash flux	80 l/m^{2}h	80 l/m^{2}h
Air flow	5 Nm^3/h	5 Nm^3/h
Air scour duration	–	–
Draining duration	–	–
Backwash top with air scour duration	60 s	60 s
Backwash bottom duration	–	–
Forward flush duration	30 s	30 s
Valve changing time	2 s	2 s
CEB water type	Filtrate	Filtrate
CEB frequency	When needed	When needed
NaClO concentration	350 mg/L	350 mg/L
Soaking time	6 min	6 min

Table 4
Reverse osmosis conditions

Parameter	Condition
Feed pressure	60 bar
Feed flow	1.42 m^3/h
Permeate flow	0.68 m^3/h
Flux	14.3 l/m^{2}h
Conversion	48%
Elements	6

although the second ultrafiltration line presents a slightly higher TMP. This also proves that operating at the base line conditions is sustainable.

Fig. 3 shows the behavior of the reference line that uses filtrated water during backwashes operating in parallel with the brine line using reverse osmosis concentrate for backwashing. It can be observed that using brine for backwashing has apparently no negative effect on the performance.

Fig. 4 shows the same comparison but in a closer scale, where the TMP reduction after a backwash can be assessed. No significant differences are observed in terms of TMP reduction after backwashes and TMP increase during filtration cycles.

Another important observation is the decrease in the number of CEBs done. This could be achieved if CEBs were done only when they are needed. This

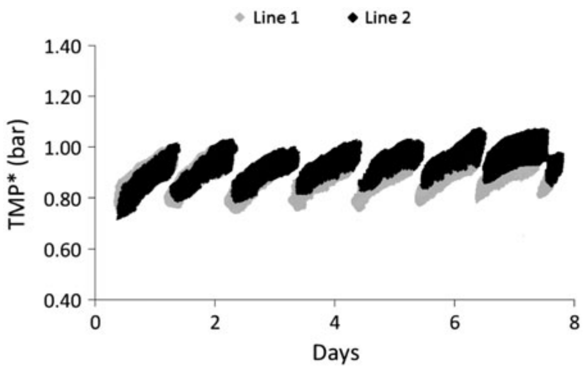

Fig. 2. Baseline conditions.

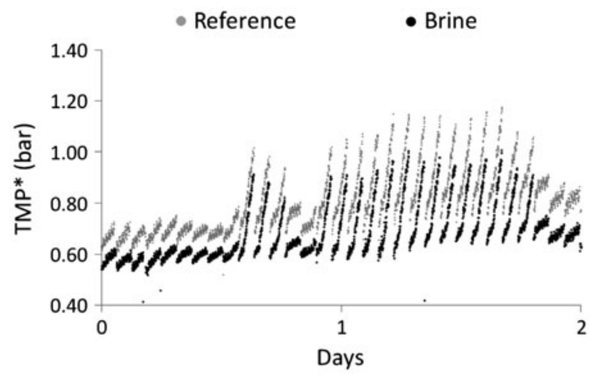

Fig. 4. First validation period (backwashes).

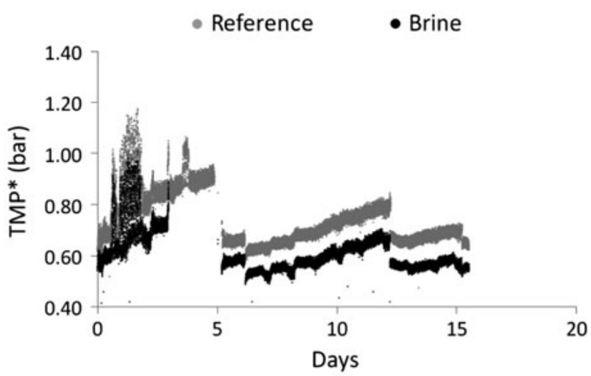

Fig. 3. First validation period.

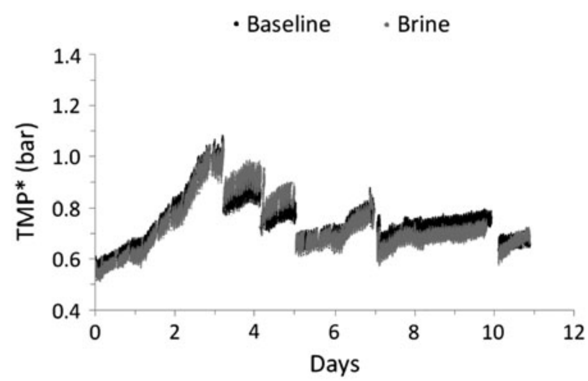

Fig. 5. Second validation period of backwash using brine and previous cleaning research findings.

leads to the decrease in the CEB frequency from one per day to one every five days. Thanks to this performance optimization, fewer chemicals are used and the frequency can be further increased.

Fig. 5 shows the validation period of using reverse osmosis brine during backwash and using only two backwash steps (brine) versus using filtrated water and the two backwash steps (baseline). From this plot, it can be seen that reverse osmosis brine can be used during backwash cleaning process using only the two steps identified previously. This is coherent with the results found in this research regarding the possibility of using brine instead of filtrated water during backwashes. It also matches the results found in the previous research, where it is proven feasible to reduce the number of backwash steps from five to two, while decreasing the backwash frequency from 30 to 90 min.

3.2. Fiber integrity

Pressure decay tests are done after each validation period to control the fibers integrity of the ultrafiltration modules. For the first operating period, after 10 min, the air pressure of the pressure decay test went down from 2.02 to 2.00 bar. This means a pressure loss of 2 mbar/min. For the second validation period, after 10 min, the air pressure of the pressure decay test went down from 2.05 to 2.04 bar. This represents a pressure loss of 1 mbar/min. These results show excellent fiber integrity according to pressure decay method described in [19]. Moreover, no broken fibers were detected over the whole experimental period. It is worth pointing out that both ultrafiltration modules were opened after the trials and no scaling or solid precipitates were observed.

3.3. TMP modeling

With all the gathered data, a model is proposed in order to predict the normalized TMP evolution over time. Fig. 6 shows the correlations obtained to predict the normalized TMP increase during the filtration cycle, the normalized TMP decrease during the backwash cycle, and the normalized TMP decrease during the CEB cycle.

Table 5 summarizes the equations obtained with their regression coefficients. It can be assessed that the filtration cycles' equations are quite similar and they show a good fit. The backwash reducing equation is even slightly more powerful for the brine line and both equations also present a good fit. CEBs equations are a little bit different, due to the fact that the reference line presents always a higher TMP than the brine line.

3.4. Model validation

The obtained model is validated with the experimentally obtained data. Brine data obtained is used to validate the model. Using reverse osmosis brine data for validating the model is preferred since it allows higher efficiency rates and lower cost compared to using filtrate during backwashes. Fig. 7 shows the comparison between the experimental data from the brine line and the model obtained from the brine line. As it can be assessed, the model is able to predict the TMP evolution of the first three days, but fails to predict the TMP increase experienced above this date. This might be due to the decrease in the CEB frequency, passing from one CEB per day to one CEB every five days. This optimization might lead to biogrowth taking place in the ultrafiltration fibers that lead to biofouling. In order to predict the biofouling effect, more data with longer times will be needed.

3.5. Efficiency assessment

Table 6 shows the different phases of the ultrafiltration advance cleaning research. Phase 1 establishes the baseline for this work with a previous optimization research, which leads to operate with filtration cycles of 30 min and five backwash steps [12]. Phase 2 focuses on reducing the number of the backwash steps to two steps as described in [4]. Phase 3 focuses on decreasing the backwash frequency to 90 min but keeping the five backwash steps as described in [13]. Phase 4 focuses on decreasing the backwash frequency to 90 min and reducing the backwash steps to two as described in [14]. Phase 5 uses the same conditions as phase 3 but using reverse osmosis brine for backwashing and depicts the experimental part of this work. Once the proof of the concept of using brine during backwash is validated, it is possible to decrease the number of backwash steps to two as demonstrated in [14]. Therefore, Phase 6 shows the ideal situation where the number of backwash steps is reduced to two, reverse osmosis brine is used during backwashes,

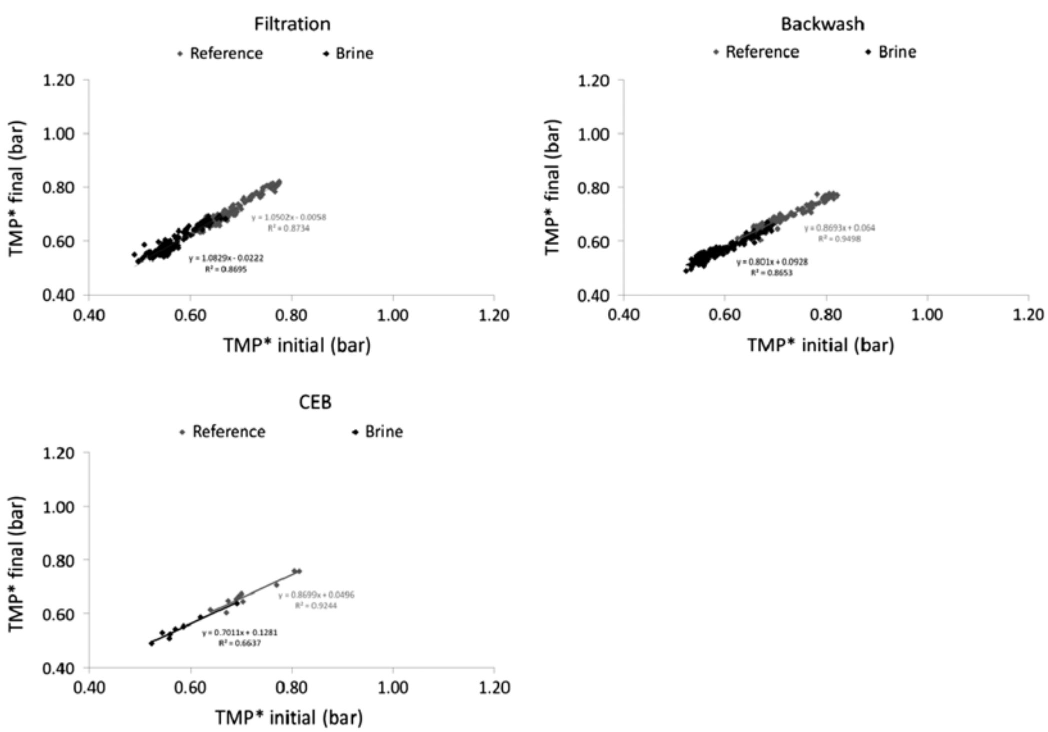

Fig. 6. Correlation between the initial and final TMP in a filtration cycle (top left), a backwash cycle (top right), and CEB cycle (bottom).

Table 5
TMP correlations in filtration, backwash, and CEB cycles

	Filtration	Backwash	CEB
Reference	$TMP_{F_f} = 1.050\,TMP_{F_0} - 0.001$	$TMP_{BW_f} = 0.869\,TMP_{BW_0} + 0.064$	$TMP_{CEB_f} = 0.870\,TMP_{CEB_0} + 0.050$
r^2	0.87	0.95	0.92
Brine	$TMP_{F_f} = 1.083\,TMP_{F_0} - 0.022$	$TMP_{BW_f} = 0.801\,TMP_{BW_0} + 0.092$	$TMP_{CEB_f} = 0.701\,TMP_{CEB_0} + 0.128$
r^2	0.87	0.87	0.66

Table 6
Different cleaning research phases

Phase	Freq (min)	BW steps	Cleaning	AS (s)	D (s)	BWT+AS (s)	BWB (s)	FF (s)
1	30	5	Filtrate	30	30	30	30	30
2	30	2	Filtrate	–	–	30	–	30
3	90	5	Filtrate	30	30	30	30	30
4	90	2	Filtrate	–	–	60	–	30
5	90	5	Brine	30	30	30	30	30
6	90	2	Brine	–	–	60	–	30

the backwash frequency is decreased to 90 min, and the CEB frequency is reduced to one every five days.

Table 7 depicts the efficiency rates together with the availability and recovery rates for each cleaning research phase. The CEC is also depicted. It can be seen that the efficiency is increased from 88% at the starting of this research to 98% at the end of this research, which represents a 12% relative increase. Moreover, the CEC is reduced from 0.32 mg/L at the beginning of this research to 0.28 mg/L at the last phase of this research. It is worth pointing out that if a CEB is done every five days instead of every day, the CEC can be reduced in Phase 6 from 0.283 to 0.057 mg/L, which represents a 10% decrease.

Table 8 summarizes the number of backwashes done per day, together with the total filtration time per day, the total backwash time per day, the filtrated water consumed per day, and the net water produced per day. It can be seen that the backwash done per day is reduced from 44 to 16, which is a 63% decrease. Filtration time is extended from 1,316 to 1,414 min/d, which represents a 7% increase. Backwash time is reduced from 124 to 26 min/d, which represents a 79% decrease. Filtrate water consumed is reduced from 2.11 to 0, which simplifies the process. To sum up, total net water produced is increased from 48.7 to 54.5 m^3/d, which represents a 12% increase.

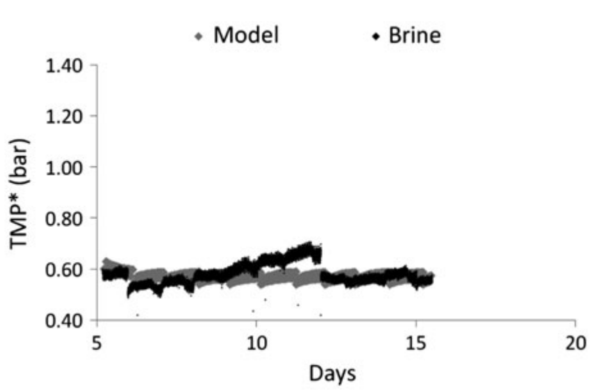

Fig. 7. Model validation.

3.6. Cost assessment

Table 9 shows the cost evolution between each ultrafiltration advance cleaning research phase within this research. Each cost is divided into each stage of a desalination plant. Each stage is divided according to its Capex and Opex costs. The stages are the intake, the ultrafiltration pretreatment, the intermediate filtration between ultrafiltration and reverse osmosis, the reverse osmosis trains, the brine discharge, and the final purification treatment. Moreover, the general costs, the contingency costs, and the profits are also taken into account. Finally, the total costs reflect the sum of the previously detached categories. It must be noticed that the costs are expressed in terms of USD cents per cubic meter of produced drinking water. Therefore, it refers to reverse osmosis filtrate and not to ultrafiltration filtrated water. Phase 5 is excluded from the cost evaluation since this phase is only intended to be a proof of the concept of using brine during backwashes. Therefore, once it is validated,

Table 7
Availability, recovery, and efficiency yields

Phase	Freq (min)	Steps	Cleaning	Availability (%)	Recovery (%)	Efficiency (%)	CEC (mg/L)
1	30	5	Filtrate	91.4	96.2	87.9	0.316
2	30	2	Filtrate	96.4	98.1	94.5	0.294
3	90	5	Filtrate	96.9	98.7	95.7	0.290
4	90	2	Filtrate	98.2	98.7	97.0	0.286
5	90	5	Brine	96.9	99.9	96.9	0.287
6	90	2	Brine	98.2	100.0	98.2	0.057

Table 8
Water saved and water produced balances

Phase	Freq (min)	Steps	Cleaning	BW cycles (#/d)	Filtration time (min/d)	BW time (min/d)	Filtrated water consumed (m^3/d)	Net water produced (m^3/d)
1	30	5	Filtrate	43.9	1,316	124	2.11	48.7
2	30	2	Filtrate	46.2	1,388	52	1.06	52.4
3	90	5	Filtrate	15.5	1,396	44	0.70	53.1
4	90	2	Filtrate	15.7	1,414	26	0.70	53.8
5	90	5	Brine	15.5	1,396	44	0.04	53.7
6	90	2	Brine	15.7	1,414	26	0.00	54.5

this technology can be integrated in the previously researched technologies. Fig. 8 visually depicts this information.

Table 10 summarizes the information contained in Table 9 for each phase of the ultrafiltration advance cleaning research. It only takes into account the ultrafiltration step. Moreover, information is condensed into Capex, Opex, and Total costs. Costs are referred as USD cents per cubic meter of final drinking water produced. Fig. 9 visually depicts this information. Thanks to the optimization performed during this research, a 7.1% cost reduction is achieved in the ultrafiltration stage.

Table 11 summarizes the information contained in Table 9 for each phase of the ultrafiltration advance cleaning research. It takes into account the whole

Table 9
Desalination cost (cUSD/m) divided by stage for each phase

Phase	1	2	3	4	6
Intake and primary pretreatment CapEx	5.39	5.33	5.30	5.30	5.26
Intake and primary pretreatment OpEx	1.36	1.33	1.32	1.32	1.30
Membrane filtration CapEx	3.92	3.78	3.76	3.73	3.71
Membrane filtration Opex	2.16	2.04	2.01	1.99	1.94
Inter pretreatment—RO section CapEx	0.34	0.33	0.33	0.33	0.33
Inter pretreatment—RO section OpEx	0.39	0.38	0.38	0.38	0.36
RO (multiple stages) CapEx	13.57	13.57	13.57	13.57	13.57
RO (multiple stages) OpEx	23.04	23.04	23.04	23.04	23.04
Brine outfall & final sanitization CapEx	1.95	1.91	1.90	1.90	1.88
Brine outfall & final sanitization OpEx	0.33	0.33	0.33	0.33	0.33
General cost CapEx	8.05	8.05	8.05	8.05	8.05
General cost OpEx	3.87	3.83	3.82	3.82	3.80
Contingency and profit CapEx	5.16	5.12	5.11	5.11	5.09
Contingency and profit OpEx	1.87	1.86	1.85	1.85	1.85
Total	71.39	70.89	70.77	70.73	70.51

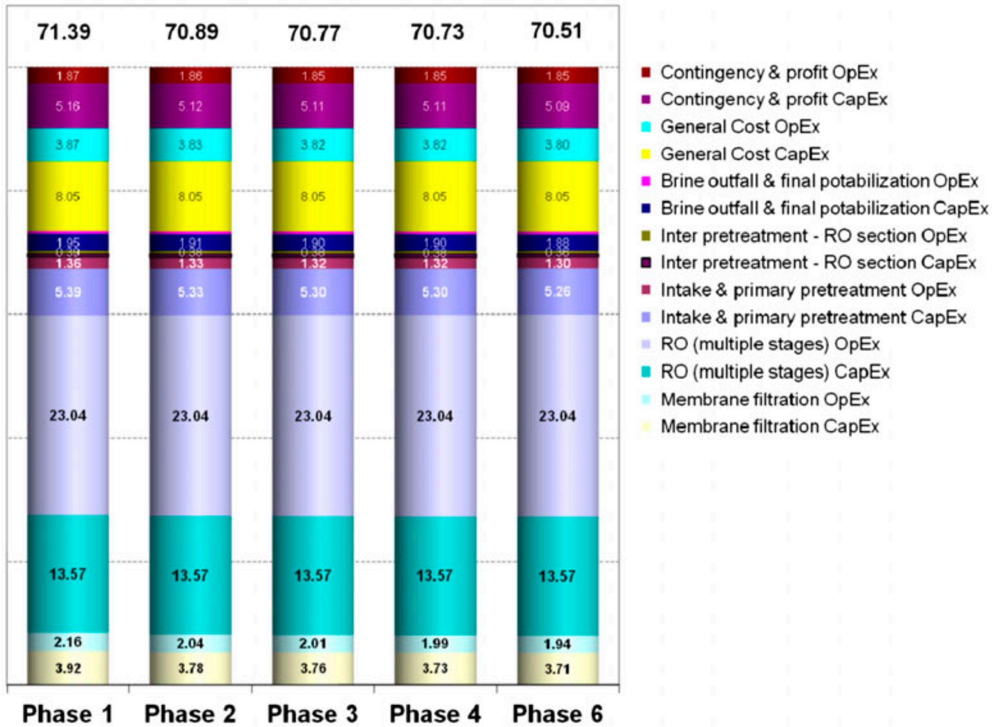

Fig. 8. Desalination cost (cUSD/m) divided by stage for each phase.

Table 10
Ultrafiltration stage cost

Phase	Freq (min)	Steps	Cleaning	OPEX (cUSD/m^3)	CAPEX (cUSD/m^3)	Total cost (cUSD/m^3)
1	30	5	Filtrate	3.92	2.16	6.08
2	30	2	Filtrate	3.78	2.04	5.82
3	90	5	Filtrate	3.76	2.01	5.77
4	90	2	Filtrate	3.73	1.99	5.73
6	90	2	Brine	3.71	1.94	5.65

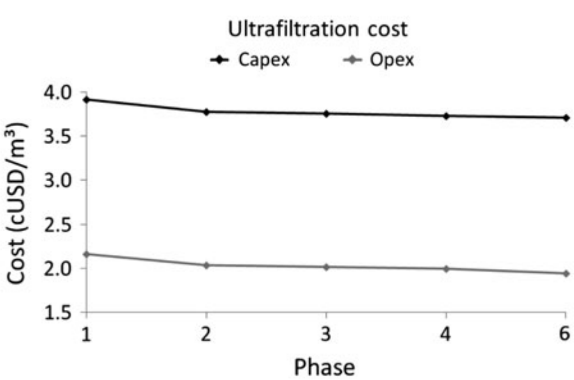

Fig. 9. Ultrafiltration cost.

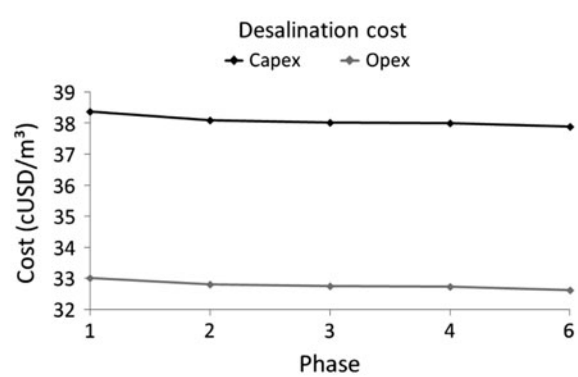

Fig. 10. Desalination cost.

Table 11
Desalination cost

Phase	Freq (min)	Steps	Cleaning	OPEX (cUSD/m^3)	CAPEX (cUSD/m^3)	Total cost (cUSD/m^3)
1	30	5	Filtrate	38.4	33.0	71.4
2	30	2	Filtrate	38.1	32.8	70.9
3	90	5	Filtrate	38.0	32.8	70.8
4	90	2	Filtrate	38.0	32.7	70.7
6	90	2	Brine	37.9	32.6	70.5

desalination process. Moreover, information is condensed into Capex, Opex, and Total costs. Costs are referred to as USD cents per cubic meter of final drinking water produced. Fig. 10 visually depicts this information. Thanks to the optimization performed during this research, a 1.2% cost reduction is achieved in the whole desalination process.

4. Conclusions

Ultrafiltration technology is proven to be a cost-effective solution to provide high-quality water to reverse osmosis elements. Among its benefits are its low footprint and high-quality filtered water without colloids, bacteria, and viruses regardless of the water composition. This paper gives an insight on how DOW™ ultrafiltration membranes can be synergistically combined with DOW FILMTEC™ reverse osmosis elements for seawater desalination. This collaboration between these two technologies has the effect to maximize the efficiency of the ultrafiltration process from 88 to 98%. This is achieved using reverse osmosis concentrate to backwash ultrafiltration membranes as well as leveraging the previous findings of the ultrafiltration advanced cleaning research program. This synergic is validated through a 15-d period. Moreover, an attempt is made to model the long-term performance of the ultrafiltration process using such conditions. This represents filtrating 96 min extra per day and a reduction of 100% in the filtrated water used during backwashes. The CEC is also drastically reduced from 0.28 to 0.06 mg/L NaClO thanks to the optimization of the CEB frequency from one CEB per day to one CEB every five days. This optimized conditions accounts for a 7.1% savings in the ultrafiltration step and for a 1.2% savings in the whole desalination process.

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