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High Efficiency Operation of Pressurized Ultrafiltration for Seawater Desalination Based on Advanced Cleaning Research

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ABSTRACT: This paper discusses a method to operate polyvinylidene difluoride (PVDF) fibers based on outside-in pressurized ultrafiltration (pUF) membranes at high efficiency used as a pretreatment in seawater desalination. Backwash sequence was initially identified as the key contributor to the process efficiency yield. Backwash duration is reduced from 170 to 100 s, eliminating three redundant cleaning steps from an original sequence of five steps. Backwash frequency is decreased from once every 30 min to once every 90 min. These two optimizations result in an efficiency increase of 10% (from 88% to 97%). Thanks to this higher efficiency operation, it is possible to save 1.4 m^3 of ultrafiltrated water per day and filtering 96 extra minutes per day. A 14 days side by side validation is performed to validate the optimized conditions. In addition, the data is analyzed in order to prove that both backwashes have the same cleaning strength in reducing the trans-membrane pressure (TMP). A model to predict TMP evolution over time is presented and validated against the real plant performance during the validation period. This model is based on analyzing TMP increase during filtration cycle, TMP recovered during backwash cleaning and TMP recovered during chemical enhanced backwash (CEB).

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 that enable a sustainable production of water.[1] Key benefits associated to 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, and some total organic carbon. Even more importantly, the ability to reliably provide good quality filtrate water to the downstream reverse osmosis are the most remarkable benefits 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 to 80 min.[3] Between two filtration cycles, a backwash (BW) will occur to enable the cleaning of the fibers and, consequently, a reduction in the trans-membrane pressure (TMP) accumulated during the filtration. A second type of cleaning, which takes place with a lower frequency compared to 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 to the backwash and also by the use of chemicals.[3−12] 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 to a CEB.[3]

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.[3] After the first improvement phase done in Barcelona, the efficiency of DOW Ultrafiltration was increased to 88%.[3]

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%.[4]

Simultaneously, previous investigations focused on reducing the backwash frequency in order to raise the ultrafiltration efficiency to 95%. The experiments were done keeping the 5 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 aim of this work is to integrate the different pressurized ultrafiltration advance cleaning researches described in refs 4 and 13, integrating in a same operation protocol the reduction in the number of backwash steps from five steps to two steps and reducing the backwash frequency from 30 to 90 min. So, combining both approaches, the efficiency representing the total ultrafiltration process yield can be increased to a very high level. Therefore, the hypothesis of this investigation is that the ultrafiltration can be operated in a stable way and sustainably by operating with a backwash frequency of 90 min and only using the two main backwash steps previously identified as being the most effective in cleaning the ultrafiltration membrane. Doing this, the efficiency can be increased even higher, which ultimately can be translated into cost savings as more water is produced with the same amount of time.

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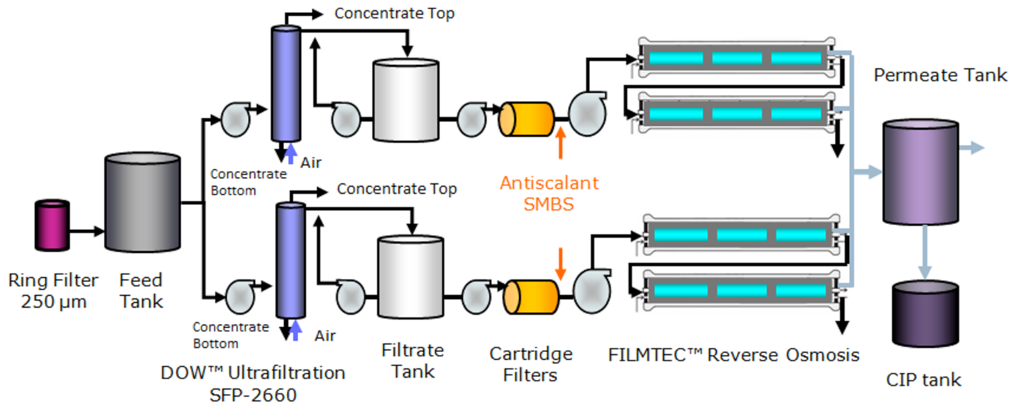

Figure 1. Ultrafiltration and seawater reverse osmosis desalination plant.

Backwash consumes more time per day when compared to CEB and CIP, as it is repeated more often. Therefore, it is identified as the first cleaning process to be improved in order to increase the efficiency of the ultrafiltration process.

2. EXPERIMENTAL PROCEDURES

2.1. Unit Description. This research is done in an experimental containerized seawater desalination plant. This unit represents one of the twenty experimental units that Dow Water & Process Solutions has in its Global Water Technology Development Center in Tarragona, Spain. Figure 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 the reverse osmosis used are DOW FILMTEC SW30XLE-4040 membranes.

2.2. Ultrafiltration Membranes. These two ultrafiltration modules used are characterized by having a diameter of 165 mm (6.5 in.) and a length of 1500 mm (59.1 in.). The fibers are made of hydrophilic polyvinylidene difluoride (PVDF) polymer, which is mechanically and chemically resistant. With this technology, it is possible to increase the fiber permeability and make it more fouling resistant. These fibers have a nominal pore size of 30 nm with a 0.7 mm inner diameter and an outside diameter of 1.3 mm. The module has a total active area of 33 m^2 (355 ft^2). DOW Ultrafiltration modules operate following an outside-in configuration. This enables operating the membranes using air scour, which helps clean the fibers.

2.3. Seawater Characterization. Seawater from the Mediterranean Sea taken from Tarragona Harbor is used for this research. Water inorganic composition is analyzed as a reference at the beginning of the experiment, having a Total Dissolved Solids (TDS) salt content of 39 252 mg/L (ion chromatograph). Table 1 depicts the total ionic seawater characterization. Water organics are analyzed every 4 days during the whole experimental period. Total organic carbon (TOC) has an average value of 1.15 ± 0.19 mg/L (UNE-EN 1484:1998), total suspended solids (TSS) has an average value of 8.29 ± 5.07 mg/L (UN-EN 872:2005), and turbidity (TB) has an average value of 3.11 ± 2.63 Nephelometric Turbidity Unit (NTU) (ISO 7027). This analysis is done in the Water Analytical Laboratory that Dow Water & Process Solutions has in its Global Water Technology Development Center located in Tarragona, Spain.

Table 1. Seawater Ion Characterization

ions	concn. (mg/L)
potassium (K)	446
sodium (Na)	11 941
magnesium (Mg)	1483
calcium (Ca)	465
strontium (Sr)	10
carbonate (CO_3)	4
bicarbonate (HCO_3)	138
chloride (Cl)	21 640
fluoride (F)	1
sulfate (SO_4)	3045
boron (B)	5
bromide (Br)	74

2.4. Normalization Equations. The normalized (TMP*) is calculated multiplying the measured TMP by the temperature correction factor (TCF) as described by eq 1.

$$\text{TMP}^* = \text{TCF} \times \text{TMP} \qquad (1)$$

The purpose of the temperature correction factor 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.[14] Therefore, different TMP values obtained at different temperatures can be compared and transported to the same reference temperature of 25 °C.

$$\text{TCF} = \frac{10^{(247.8/25+273.16-140)}}{10^{(247.8/T+273.16-140)}} \qquad (2)$$

2.5. Efficiency Equations. Efficiency is defined as the net yield of the ultrafiltration process. It is obtained 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.

$$\text{Efficiency} = \text{Availability} \times \text{Recovery} \qquad (3)$$

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.

$$\text{Availability} = \frac{t_{\text{filtrating}}}{t_{\text{total}}} \qquad (4)$$

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Water product recovery measures net water produced. Filtrated water consumed during backwashes and CEBs is discounted. This yield is calculated using eq 5.

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

2.6. Cleaning Methods. A typical backwash consists of five small steps.[15] The first step is the air scour, where air is blown inside an ultrafiltration membrane at 12 N m^3/h. Air makes the fiber shake. This is achieved by opening the air feed valve, which allows air enter the module, and the concentrate valve, which allows air to exit the membrane. The second step, the draining step, empties the module. Draining helps removing all the fouling that have detach from the hollow fibers and are placed in the water. This is achieved by emptying the concentrate valve, so that air can enter the module, and opening the feed valve, where wastewater exits the module. The third step is the backwash top with air scour. Backwash top with air scour combines the pore unblocking effect of a backwash with the aeration shacking effect. This is achieved by opening the filtrate valve while using the backwash pump and opening the concentrate valve so that waste can exit. Meanwhile, the air valve is open so that air can be blown inside the element while the backwash takes place. The fourth step is the backwash bottom, which also unblocks fibers pores. This is achieved by opening the filtrate valve while using the backwash pump and opening the feed valve so that waste can exit. The fifth step is the forward flush, where feedwater is pumped inside the module, having the filtrate valve closed and the concentrate valve open. This creates a shear effect above the membrane surface, which helps eliminating fouling. A typically chemical enhanced backwash (CEB) consists of the same steps than the backwash sequence but with a NaClO injection during the backwash sequence, followed by a soaking time.[3−12] This gives time for the chlorine to eliminate all the bacteria present inside the element that could cause biofouling.

2.7. Validation. The hypothesis of this research is that a high efficiency operation of the ultrafiltration process can be achieved through further optimizing the backwash sequence. This is achieved combining the reduction of the backwash steps from five to two,[4] and the optimization of its frequency from 30 to 90 min.[13] This is achieved by assessing the total backwash time per day the membrane needs to be cleaned effectively. Reducing the backwash duration and its frequency contributes in adjusting the backwash duration per day.

In order to validate the hypothesis of this research, new UF modules are installed. The first phase is verifying these two modules that will be used later are actually performing in a similar way under the same operating conditions. For this purpose both ultrafiltration lines are identically operated for seven days according to the conditions depicted in Table 2. Moreover, this trial would also validate the conditions where the ultrafiltration is operated with a backwash every 90 min and with the five main backwash steps (air scour, draining, backwash top with air, backwash bottom, and forward flush), as stated in the literature by Garcia-Molina.[13] In order to prevent biofouling, a CEB is done on a daily basis.

After the initial validation, the first ultrafiltration line is operated according to the optimized alternative conditions, while the second ultrafiltration line is operated with the reference conditions, as depicted in Table 2. The hypothesis of this work is that the optimum conditions will have the same cleaning strength than the nonoptimized ones. This statement is made since the optimum conditions have the same backwash total time per cleaning (60 s from backwash top with air scour) than the nonoptimized one (30 s from backwash top with air scour + 30 s from backwash bottom). Therefore, the benefit that the optimized conditions present is that it will last less time than the nonoptimized conditions. This happens because no initial air scour (30 s) and no draining step (30 s) is done in the optimized conditions. This initial Air scour is not needed in the optimized conditions, since the 60 s of aeration done during the backwash top with airs sour are equivalent than doing an initial air scour of 30 s and afterward a backwash top with air scour of 30 s in the nonoptimized conditions. Following this strategy, the draining step is not needed since it adds no value in the membrane cleaning. To summarize, and as it can be seen in Table 2, the cleaning optimized conditions will take 1 min 30 s to clean, while the nonoptimized cleaning conditions will need 2 min 30 s. These shorter backwash cycles represent a reduction in the time needed by each backwash to be completed of at least 40%. This value could be even higher if the time each pump takes to ramp and each valve takes to go from one cleaning step to the other are taken into account.

Table 2. Reference and Optimum Conditions

param.	reference	optimum
flux	70 L/(m^2 h)	70 L/(m^2 h)
backwash frequency	90 min	90 min
backwash flux	80 L/(m^2 h)	80 L/(m^2 h)
air flow	12 N m^3/h	12 N m^3/h
air scour duration	30 s	
draining duration	30 s	
backwash top with air scour duration	30 s	60 s
backwash bottom duration	30 s	
forward flush duration	30 s	30 s
valve changing time	2 s	2 s
CEB frequency	24 h	24 h
NaClO concn.	350 mg/L	350 mg/L
soaking time	6 min	6 min

2.8. TMP Modeling. The TMP evolution over time is modeled to predict the fouling trend in the long term operation. This is achieved 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 the 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 which enable the prediction of the long-term TMP evolution. Thanks to the model, the engineer will be able to decide which operating conditions are more adequate to its installation depending on each type of cost like the cost of chemicals, the cost of electricity and the cost of manpower.

3. RESULTS AND DISCUSSION

3.1. Validation. Figure 2 shows the validation of both lines operated at the same conditions. No major differences between both ultrafiltration lines and modules are seen, although the second ultrafiltration line presents a slightly higher TMP. This

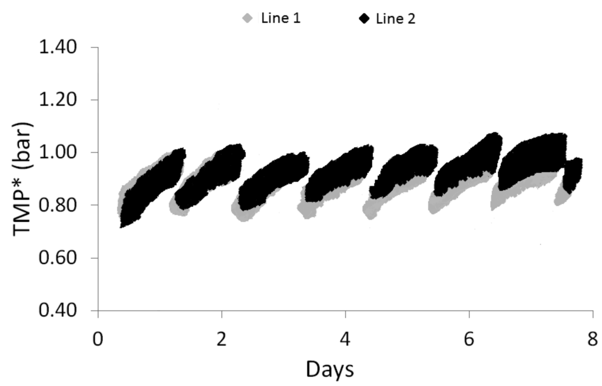

Figure 2. Reference conditions.

also proves that operating at the baseline conditions is sustainable.

In order to test if the hypothesis stated in this research is correct and the optimum conditions are sustainable, a validation period of 14 days is completed. Figure 3 depicts the TMP evolution over time. Observing this plot, it can be seen that both lines start at the same TMP level between 0.60 and 0.70 bar. After this, fouling takes places during the filtration cycle. Therefore, as ultrafiltration operates at constant filtrate pressure, TMP increases. It is observed that fouling increases over time at the same rate in both lines. After 24 h of operation, a CEB takes place. The chemical cleaning reduces the TMP from a value between 0.9 and 1.0 bar, to the initial TMP values of 0.60 and 0.70 bar. Thus, it can be seen that both lines follow the same fouling increase patter during filtration cycles and the same fouling decrease pattern after chemical cleanings. This might suggest that the optimum conditions identified in this research are thus validated. These results show the same fouling trend observed in the literature by Gilabert Oriol.[4] Combining both researches it can be assessed that the TMP increases with a rate of 0.25 bar per day. Moreover, thanks to the CEB, the TMP is fully recovered to its initial value. As the TMP is controlled kept constant below 1 bar, the operation is considered sustainable. The benefit associated with a high efficient and optimized backwash, enables the operation of the modules at a high efficiency, maximizing the total net flux produced.

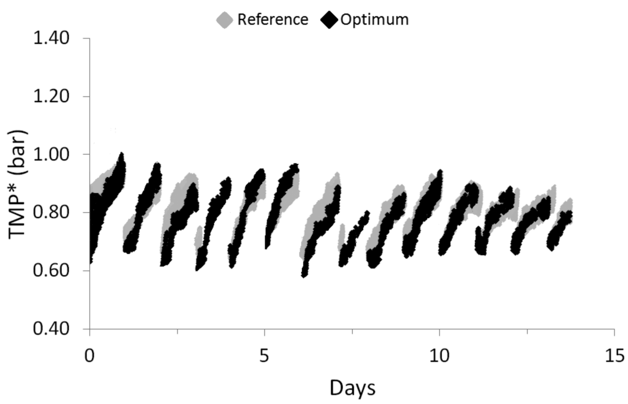

Figure 3. Validation period.

3.2. TMP Modeling. Once the hypothesis of this work is validated, a model is proposed to predict the TMP within boundaries and conditions in which the unit is operating. In order to build the model, the TMP values at the beginning and at the end of the filtration cycle are plotted in order to assess if any correlation exist between these values. The same is done for the TMP before a backwash and after the backwash, as well as for the CEB cleaning protocol. Figure 4 depicts the linear relationship between the TMP at the beginning and at the end of each ultrafiltration cycle. From these plots, it can be seen that the model is valid for TMP values between 0.60 and 0.90 bar. Moreover, it can be observed that both lines present the same relationships as both lines always overlap themselves. This might indicate that fouling behavior is the same in both lines, regardless the backwash cleaning conditions. Also, it can be seen that the model is validated since the fouling relationships observed have a good match with the plant operating points. This figure also shows that in a filtration cycle, TMP will always be increased due to fouling, while in a cleaning cycle such as the backwash and the CEB, TMP will always be recovered. This model is built in order to analyze the data through the study of the different batch cycles that occur during the operation of the ultrafiltration. Analyzing the data in this way helps obtaining a general picture of the process, since the backwash efficiency is separated from the filtration TMP increase and from the CEB cleaning efficiency.

The correlations obtained are summarized in Table 3, where TMP_0 represents the TMP at the beginning of each filtration cycle and corresponds to the end of previous backwash cycle. TMP_f represents the TMP at the end of each filtration cycle and corresponds to the beginning of the next backwash cycle.

Using the equations shown in Table 3, a model is built in order to predict the TMP over time. As it can be seen when analyzing the data, both filtration cycles are almost identical. So, taking into account the two extreme scenarios where the TMP is at is lower value (0.60 bar) and the TMP is at its higher value (1.00 bar) among the experimental data collected, the difference in terms of percentage TMP is only −0.9% and 3.8%, respectively. In addition, similar performance is observed when line 1 and line 2 operate at the same conditions (Figure 2). Moreover, observing the backwash TMP equations, it can be assessed that the reference backwash and the optimized backwash are almost identically. These two analyses might suggest the improvement made in the backwash sequence is effective as both types of backwash have the same cleaning power. Since both equations have the same cleaning strength, it is more economically viable to use the optimum conditions since the same cleaning effect is achieved with a shorter amount of time. This represents a time reduction during the backwash cleaning cycle of 42%, since the backwash time is reduced from 2 min 50 s to 1 min 38 s.

However, it can be observed that the CEB presents a low regression coefficient (r^2) value. This means that regardless the final TMP value of the filtration cycle, the TMP will always be restored to its initial value. The equation to predict the TMP reduction during the CEB cycle is therefore calculated averaging all the TMP final points and has a value of 0.68 bar. This might suggest that the dosage concentration of 350 ppm of NaClO can be minimized to a lower value as the chemical concentration is possibly overdosed, or the CEB frequency can be reduced.

After analyzing all data obtained, Table 4 summaries the equations obtained to predict the TMP evolution over time at the conditions the unit has been operating.

3.3. Model Validation. Once the modeling equations are obtained, the model is validated with the experimental data

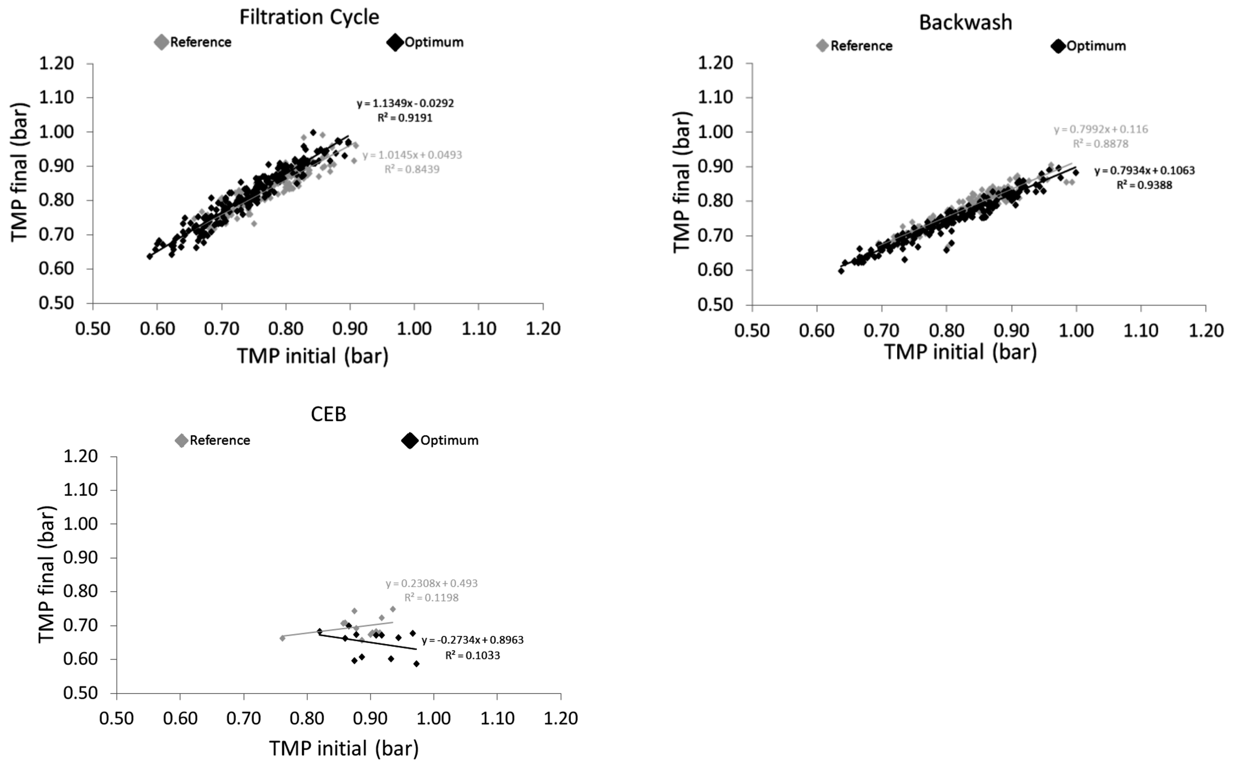

Figure 4. Correlation between the initial and final TMP in a filtration cycle (top left), backwash cycle (top right), and CEB cycle (bottom).

Table 3. TMP Correlations in Filtration, Backwash, and CEB Cycles

	filtration	backwash	CEB
optimum	$TMP_{F_f} = 1.135TMP_{F_o} - 0.029$	$TMP_{BW_f} = 0.793TMP_{BW_o} + 0.106$	$TMP_{CEB_f} = -0.273TMP_{CEB_o} + 0.896$
reference	$TMP_{F_f} = 1.015TMP_{F_o} + 0.049$	$TMP_{BW_f} = 0.799TMP_{BW_o} + 0.116$	$TMP_{CEB_f} = -0.231TMP_{CEB_o} + 0.493$
average	$TMP_{F_f} = 1.075TMP_{F_o} + 0.010$	$TMP_{BW_f} = 0.796TMP_{BW_o} + 0.111$	$TMP_{CEB_f} = -0.021TMP_{CEB_o} + 0.695$
r^2	0.89	0.91	0.11

Table 4. Model Equations for the Filtration, the Backwash, and the CEB Cycle

	filtration	backwash	CEB
equation	$TMF_{F_f} = 1.075TMP_{F_0} = 0.010$	$TMP_{BW_f} = 0.796TMP_{BW_0} + 0.111$	$TMP_{CEB_f} = 0.68$

obtained during the validation period. As the reference and the optimized conditions show the same performance, the improved conditions are chosen to validate the model. Figure 5 depicts the model validation for the whole two weeks validation period, where the effects of the CEBs can be assessed. From these plots, it can be observed that the model fits accurately the real operation. The impact of the backwashes can also be assessed when zooming in a portion of Figure 5.

The present model used to evaluate the backwash and the fouling associated with it, is only valid for the given set of operating conditions. These are a filtration flux of 70 L/(m^2 h), a backwash flux of 80 L/(m^2 h), a CEB done every 24 h with a chlorine concentration of 350 mg/L, an air flow of 12 N m^3/h, a seawater feed turbidity below 5 NTU and a TMP between 0.60 and 1.00 bar. Extrapolating this model out of this range could induce misleading results. However, the filtration cycle duration could be reduced since the backwash is independent from it.

3.4. Efficiency Determination. Table 5 depicts the different phases done during the pressurized ultrafiltration cleaning research. Phase 1 was the reference established thanks to the research done in Qingdao during 2009,[3] phase 2 was the result of the research done in Tarragona during 2012,[4] while phase 3 was the reference established in parallel in Tarragona during 2012,[13] and finally, phase 4 is the result of this present research also done in Tarragona during the year 2012. It must be noticed that AS refers to the air scour step, D refers to draining step, BWT+AS refers to backwash top with air scour step, BWB refers to backwash bottom, and FF refers to forward flush. It is important to notice that all the improvements done in the operating conditions keep the same cleaning efficiency as it is assessed during the side-by-side compared with the reference.

Table 6 shows the availability, the product recovery, and efficiency yields according to each different phase of the pressurized ultrafiltration advanced cleaning research for a filtration flux of 70 L/(m^2 h), a backwash flux of 80 L/(m^2 h) and 2 s of valve changing time.

Table 7 shows for each phases of the pressurized ultrafiltration advanced cleaning research, the evolution of different parameters. These are the number of backwashes done per day, the total filtrating time per day, the total backwash time per day, the water produced per day, and the ultrafiltrated water consumed during backwashes every day. From this table, it can

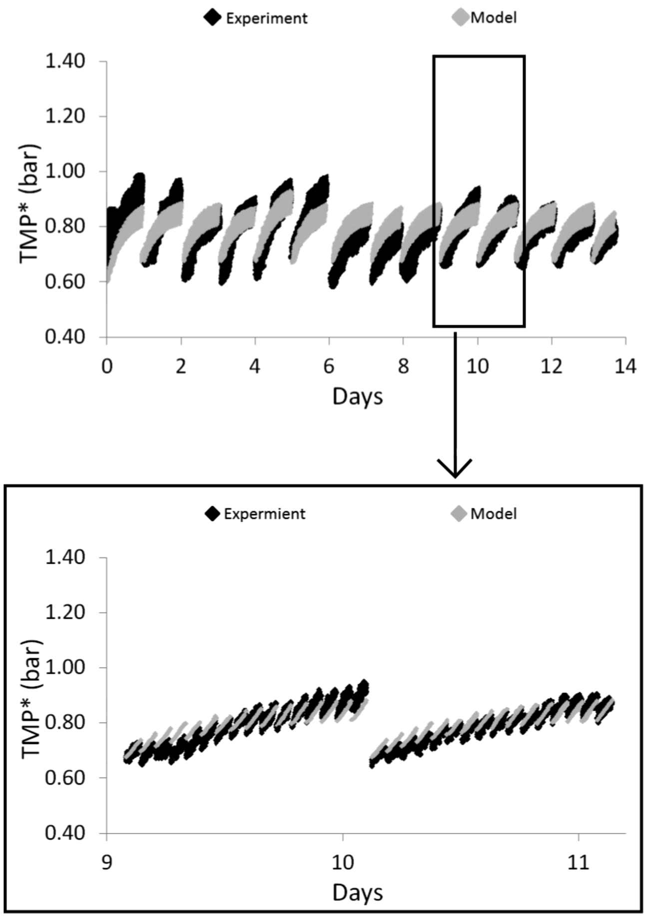

Figure 5. Model validation.

Table 5. Different Cleaning Research Phases

phase	filtration (min)	BW steps	AS (s)	D (s)	BWT+AS (s)	BWB (s)	FF (s)
1	30	5	30	30	30	30	30
2	30	2			30		30
3	90	5	30	30	30	30	30
4	90	2			60		30

Table 6. Availability, Recovery, and Efficiency Yields

phase	freq	steps	availability (%)	recovery (%)	efficiency (%)
1	30	5	91.4	96.2	87.9
2	30	2	96.4	98.1	94.5
3	90	5	96.9	98.7	95.7
4	90	2	98.2	98.7	97.0

be assessed the direct correlation between the reduction of the number of backwashes done per day and the reduction of the backwash time per day, with the efficiency increase.

Table 7. Water Saved and Water Produced Balances

phase	freq	steps	BW cycles (no./day)	filtration time (min/d)	BW time (min/d)	water produced (m^3/d)	filtrated water consumed (m^3/d)
1	30	5	43.9	1316	124	50.7	2.11
2	30	2	46.2	1388	52	53.4	1.06
3	90	5	15.5	1396	44	53.7	0.70
4	90	2	15.7	1414	26	54.4	0.70

4. CONCLUSIONS

This paper discloses a method to operate DOW Ultrafiltration membranes at high efficiency providing a good water quality of 44 mNTU to feed DOW FILMTEC reverse osmosis membranes for seawater desalination.

The backwash cleaning process is further optimized thanks to the fusion of two concepts. The first one refers to the reduction of redundant backwash step from 5 to 2 steps. The steps eliminated are the initial air scour, as an air scour is already done during the backwash top with air scour. The elimination of the draining step, since the draining effect is achieved when the forward flush step introduces new water inside the ultrafiltration module, being the water introduced at least two times the module free volume. The last step eliminated is the backwash bottom, since the backwash cleaning effect is already done in the backwash top with air scour. The second step optimized is the reduction of the backwash frequency from 30 to 90 min.

Thanks to this process optimization, the efficiency is ultimately increased from 88% to 97%. This is achieved thanks to the availability increasing from 91% to 98% and to the product recovery increase from 96% to 99%. This 10% of efficiency increase represents reducing the total backwash time from 124 min per day to 26 min per day, which represents having the unit operating 96 min extra per day. Moreover, this improvement represents savings in the water produced used for the backwash, therefore, instead of using 2.1 m^3/d, only 0.7 m^3/d are used, which represents a saving of 1.4 m^3/d.

This achievement is finally validated with a side by side operation of two ultrafiltration modules, one having a reference point with all the five backwash steps but only does a backwash every 90 min, and the other having the optimum conditions. The backwash cleaning efficiency of both conditions is assessed analyzing all the operational data. So, the TMP reductions achieved in each backwash for each condition are compared, obtaining the same backwash cleaning time per day for both conditions, but as the optimum condition uses a shorter backwash, it is concluded that the backwash efficiency of the optimum condition is higher.

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Notes

The authors declare no competing financial interest.

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