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Optimizing seawater operating protocols for pressurized ultrafiltration based on advanced cleaning research

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ABSTRACT

This paper is part of a global research project conducted by Dow Water & Process Solutions to optimize the efficiency of ultrafiltration processes. After an initial identification of the backwash as the key opportunity to increase the efficiency of the process, a study based on its optimization is developed. Main emphasis is given to the sequence and subsequent number of steps involved in the backwash. The ultimate goal is thus to increase the availability and recovery of the process while still attaining a high cleaning effect during the backwash. This optimization is done through the realization of various experiments using DOW™ Ultrafiltration SFP-2660 outside-in polyvinylidene difluoride (PVDF) membranes following an exhaustively planned factorial design of experiments. The factors being assessed are the steps normally performed during a backwash. These are the air scour (AS/D), the draining (D), the backwash top (BWT) with or without air scour, the backwash bottom (BWB) and the forward flush (FF). The responses analyzed are the calculated efficiency of the process and the experimentally obtained transmembrane pressure, which represents the fouling rate of the membrane. The results are analyzed through a formal statistical study of the analysis of the variance and are validated through 25 days of stable operation. The results show that the backwash can be simplified from an original sequence of five steps to only two steps, which are the backwash top with air scour and the forward flush without impairing the effectiveness of the cleanings. This leads to an increase in efficiency higher than 5%, which represents a decrease of 50% in the filtration inefficiency. This is achieved thanks to the reduction of the time invested for the cleanings and the decrease in the amount of water consumed.

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

1. Introduction

The ultrafiltration process is characterized, unlike reverse osmosis, by having relatively short filtration cycles given the need of 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

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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 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. 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 concentration used compared to a CEB.

Short-term cleanings such as the BW are 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 BW takes about 1 min. The BW flux varies between 70 and 300 L/h/m^2 (10/90% percentiles) and typically reflects double the operating flux. Occasionally, chemicals are used. H_2O_2 and sodium metabisulfite (SMBS) are used as BW chemicals, but were judged as less effective than chlorine. As an example, BW chemistry is evaluated comparing 25 mg/l H_2O_2 and 10 mg/l NaOCl, and the NaOCl chemistry seemed to be far more effective [1]. NaOCl has recently been the most widely used and has emerged as the standard for BW 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^3/h every 1–8 BW cycles.

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 NaOCl 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 [2], while higher concentrations are applied less frequently with a range of 12 and more hours. NaOH was tried in few occasions with and without NaOCl but was quickly dismissed due to its scaling nature [3]. In fact, precipitations have already been discovered with NaOCl, which is also a weak base [4]. In the acid CEB: most frequently, H_2SO_4 and HCl are used, occasionally also citric acid. 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 to 1:3 compared to chlorine CEBs. The chemical dosing duration in CEB steps is typically 30 s, hence shorter than the BW duration in a normal BW. 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 BW 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 "Chemical Enhanced Backwash") are the most diverse among all cleaning conditions and many different variations are described. A protocol which combined chemical dosing for only a very short time period with air bubbling has also been proposed [5]. With outside-in technology, it has also been frequently described to automatically dose chemicals to the feed, instead of the product, and recirculate [6]. Finally, the addition of chemicals to reverse osmosis permeate is described as well. A special BW protocol, involving the use of heated cleaning solution, not only in the CIP, but also in the CEB is proposed as well [7,8]. 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" [8,9]. 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 0.7 up 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 NaOCl 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.

This paper is a part of a general research project focused on maximizing the efficiency of DOW™ Ultrafiltration processes by optimizing the operating sequence, including the filtration conditions and its cleaning strategy taken into account the different backwashes, chemical enhanced BWs and cleanings in place. Among these various processes, the BW is identified as a key parameter that influences the overall efficiency of the process. Despite the relatively short duration of the BW, it can occur up to 48 times per day when done every 30 min. This involves a large amount of time out of operation. Moreover, the BW has a double negative effect from the point of view of the water produced because during the BW, water is not produced and in addition previously produced water is consumed.

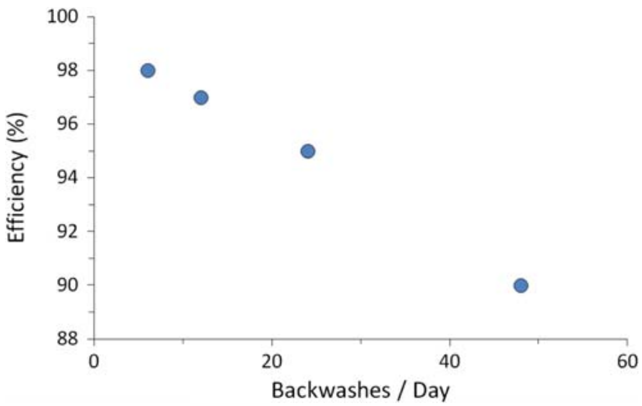

Fig. 1. Importance of BW in overall efficiency.

The impact of the BW in the overall efficiency of the process is depicted in Fig. 1, where a reduction of 50% in the number of BWs per day leads to an increase in efficiency from 90% up to 95%. The same applies if the time needed by a BW to clean the ultrafiltration fibers is reduced by a half.

Therefore, this paper is focusing on reducing the time invested for the BW sequence, while still maintaining the same cleaning effectiveness.

The steps typically included in the BW sequence are the AS/D, with a duration between 30 and 60 s; the draining (D), with a duration between 10 and 15 s; the backwash top (BWT) with AS/D, with a duration between 30 and 40 s; the backwash bottom (BWB), with a duration between 30 and 40 s; and the forward flush (FF), with a duration between 10 and 60 s.

This research is focused in the identification of those steps inside the BW sequence that have a lesser contribution to the overall cleaning efficiency of the backwash. The elimination of those steps will certainly enables higher efficiencies, which ultimately can be translated into savings in operational expenses (OPEX) and capital expenses (CAPEX).

2. Materials and methods

2.1. Installation setup

2.1.1. Installation

This research is done in the experimental containerized seawater desalination plant Dow Water & Process Solutions has in Tarragona (Spain) and is fed with Mediterranean seawater. Fig. 2 shows the scheme of the plant, which consists of two independent lines both containing ultrafiltration as a pretreatment for RO. This unit represents one of the pilot plants currently operated with various water sources in the Dow Tarragona Global Water Technological Center. The intake of the seawater supplied into this particular unit is located at the industrial harbor of the city. The pretreatment before the ultrafiltration unit includes an Amiad® Arkal disk filter of 250 µm. The ultrafiltration modules used are DOW™ UF SFP-2660 and FILMTEC™ SW30XLE-4040 are used in the RO section.

2.1.2. Ultrafiltration

In order to validate the hypothesis of this research, only one of two parallel ultrafiltration lines is used. The membrane used is a DOW™ Ultrafiltration SFP-2660 module, with a diameter of 165 mm (6.5 inches), and a length of 1,500 mm (59.1 inches). This type of module uses polyvinylidene difluoride (PVDF) fibers with a pore size of 30 nm, 0.7 mm inner diameter, and an outside fiber diameter of 1.3 mm and comprises a total surface active area of 33 m^2 (355 ft^2). DOW™ Ultrafiltration modules operate following an outside-in configuration given the advantages associated with this modus operandi such as better cleanability, lower fouling trends, the benefit of using AS/D and higher mechanical and chemical resistances.

2.2. Design of experiments

2.2.1. Experimental setup

Before starting each experiment, there is a need to ensure the membranes were not fouled. Therefore, a complete BW and CEB sequence is needed at the beginning of each experiment to ensure the transmembrane pressure is reduced to the initial levels to establish a baseline. This complete sequence includes an air scour of 30 s, a D of 10 s, a BWT combined with an air scour of 20 s, a BWB of 20 s and a FF of 15 s. After this initial backwash, a CEB that prepare does 350 mg/l of NaOCl through a BWT and has a soaking time of 6 min is needed. After this sequence, another complete BW is needed to remove residual chlorine.

Each experiment consists of five filtration cycles of 30 min each. Approximately, each experiment lasts between 2:30 and 3:00 h. The filtration flux of the ultrafiltration module is set up to 90 l/m^2 h (3 m^3/h). Between each filtration cycle, a BW at each specific given condition is performed. The operating conditions of each experiment and their set points are summarized in Table 1 and are kept constant for the whole research. In order to properly calculate the efficiency, it must be taken into account the automated valves need 2 s time to change their position.

2.2.2. Variable coding

Each experiment has its own unique BW cleaning sequence. To determine the contribution of each

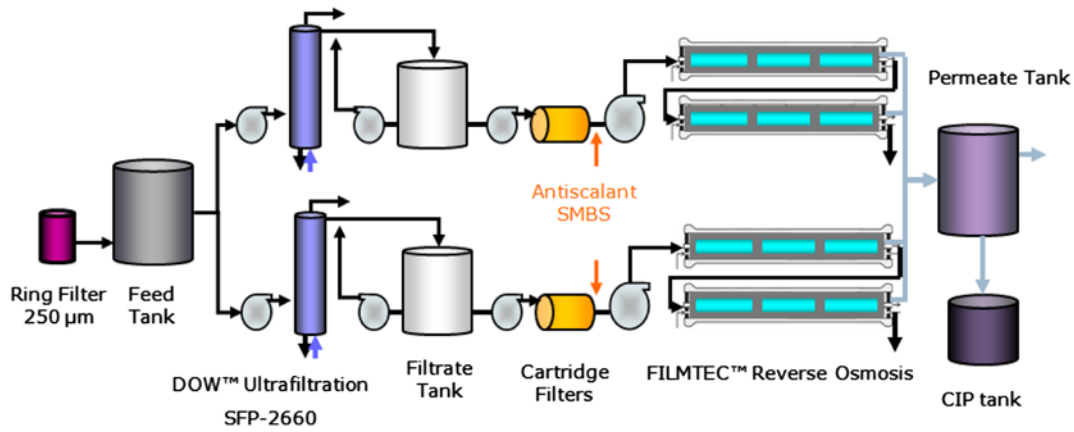

Fig. 2. Ultrafiltration and seawater RO desalination installation scheme.

Table 1
BW steps conditions

Step	Order	Time (s)	Flux ($l/m^2 h$)	Flow (m^3/h)	Flow air (m^3/h)
Air scour (AS)	1	30	–	–	20
Draining (D)	2	10	–	–	–
BWT	3	20	135	4.5	20
BWB	4	20	135	4.5	–
FF	5	15	90	3	–

cleaning step within the BW sequence to the final TMP reduction and its relationship to the overall efficiency of the ultrafiltration process, a Yes/No strategy is proposed as part of the design of experiments (DOE). Therefore, each factor is coded according to Table 2.

The variables assessed in the DOE are the different BW steps. Thus, as Table 2 shows, these factors are the air scour with and without a D afterwards, which is coded as 0, 1, 2; the BWT with and without air scour, which is coded as 0, 1, 2; the BWB, which is coded as 0, 1; and the FF which is coded as 0, 1. It is important to notice that all the variables are coded as discrete categorical variables.

Table 2
Design of experiments coding

Step	Coding	Meaning
AS/D	0	No AS/D
	1	AS/D (30 s)
	2	AS/D (30 s) + D (10 s)
BWT	0	No BWT
	1	BWT without AS/D (20 s)
	2	BW with AS/D (20 s)
BWB	0	No BWB
	1	BWB (20 s)
FF	0	No FF
	1	FF (15 s)

Once these factors are coded, different experiments are statistically designed and executed according to the coding described in Table 2. The full list of experiments is summarized in Table 3. The experiment number reflects the order in which the experiment is done as randomization is applied in order to eliminate the influence of secondary factors and time dependent events. Moreover, three center points (1 1 1 1) are done in order to assess the accuracy and the precision of the results obtained and to keep the DOE balanced.

To illustrate this coding, some examples are given. The experiment number 1 (0 0 0 0) consists of no BW cleanings between filtration cycles. Another example is experiment number 15 (0 0 1 1) where each backwash cleaning consist only of a BWB and a FF. One last example is experiment number 17 (2 2 1 1), which reflects the current state of the art where all the possible cleaning steps are done during the BW sequence. These steps are the AS/D, the D, the BWT with an AS/D, the BWB and the FF.

Table 3
Design of experiments planned

Experiment Number	AS/D	BWT	BWB	FF
1	0	0	0	0
15	0	0	1	1
4	0	1	0	1
18	0	1	1	1
24	0	2	0	0
25	0	2	0	0
22	0	2	0	1
12	0	2	1	0
28	1	0	0	1
9	1	0	0	1
23	1	0	1	0
13	1	0	1	0
21	1	1	0	0
2	1	1	0	0
16	1	1	1	1
5	1	1	1	1
10	1	1	1	1
19	1	2	1	1
7	2	0	0	1
26	2	0	0	1
20	2	0	1	1
11	2	1	0	1
14	2	1	1	0
3	2	2	0	0
17	2	2	1	1

2.3. Results evaluation

To make sure any change in the feedwater quality does not influence the response variable, the feed turbidity is monitored with a Hach Lange "1720E Turbidimeter Low Range." The filtrate turbidity is also monitored with a Hach Lange "FilterTrakTM 660sc Laser Nephelometer," which is able to measure low ranges of turbidity values. The turbidity measurements are compared with samples analyzed in the Tarragona Dow Water & Process Solutions Analytical Laboratory. The temperature is also controlled in order to assess any possible influence in the response variable.

2.3.1. TMP normalization

The response variable assessed is the normalized TMP increase (ΔTMP^*). The TMP increase is defined as the difference between the TMP at the end of the experiment (TMP_f^*) and the TMP at the beginning of the experiment (TMP_0^*), divided by the TMP at the beginning of the experiment, as defined by Eq. (1). Each TMP value obtained is the average of the first 2 min of operation once the nominal flow is achieved. The TMP increase represents the fouling ratio at which the membrane is fouled, and the ultimate goal is to minimize it keeping it as small as possible.

$$\Delta TMP^* = \frac{TMP_f^* - TMP_0^*}{TMP_0^*} \tag{1}$$

The normalized (TMP^*) is calculated by multiplying the measured TMP by the temperature correction factor (TCF) as described by Eq. (2).

$$TMP^* = TCF \cdot TMP \tag{2}$$

The purpose of the temperature correction factor is to take into consideration the effect of the temperature (T) in Celsius grades and its influence in the viscosity of water, as described by Eq. (3) [10]. Therefore, different TMP values obtained at different temperatures can be compared and transported to the same reference temperature of 25°C.

$$TCF = \frac{10^{\left(\frac{247.8}{25+273.16-140}\right)}}{10^{\left(\frac{247.8}{T+173.16-140}\right)}} \tag{3}$$

2.3.2. Efficiency calculation

The efficiency is defined as the net yield of the ultrafiltration process. It is obtained by multiplying the raw water recovery yield by the availability yield. The efficiency is used to make a fair comparison between these two parameters, making sure both the time and the water produced are taken into consideration to calculate the overall process yield. This yield is calculated by Eq. (4).

$$\text{Efficiency} = \text{Availability} \cdot \text{Recovery} \tag{4}$$

The availability measures the fraction of time that the ultrafiltration module is producing water. Therefore, the time which it uses to execute the various types of cleaning protocols (especially the backwash, but also the CEB and CIP) is discounted. This yield is calculated by Eq. (5).

$$\text{Availability} = \frac{t_{\text{filtrating}}}{t_{\text{total}}} \tag{5}$$

The raw water recovery measures the water produced. Therefore, the water consumed by the BWs including the FF and the CEB is discounted. This yield is calculated by Eq. (6).

$$\text{Recovery} = \frac{V_{\text{water produced}} - V_{\text{CEB}} - V_{\text{BW}}}{V_{\text{water produced}} + V_{\text{FF}}} \tag{6}$$

2.4. Hypotheses testing

The results obtained from the design of experiments are statistically evaluated through the different hypotheses testing using the analysis of variance (ANOVA) methodology. Therefore, each categorical variable representing the status of each different BW step is tested for statistical significance in each hypothesis test against the defined confidence level set to 0.95 and the significance level set to 0.05. This confidence level indicates a 95% of probability of being right with the conclusions extracted. This hypotheses contrast is performed using JMP® Pro 9.0.3 (SAS Institute Inc.) software.

2.4.1. Variances comparison

The variance measures how far the data are spread out, thus measuring the average distance between each set of data points and their mean value, equal to the sum of the squares of the deviation from the mean value. Therefore, before checking the statistical significance of each BW step, a contrast of hypotheses against a significance level of 0.05 is done in order to check if the variances are the same for each categorical variable. Table 4 summarizes the different null and alternate hypothesis to be validated according to the Brown-Forsythe Test [11]. If the variances are the same, a conventional ANOVA test will be done in order to compare means, while if they are not the same, a Welch ANOVA test would be needed.

2.4.2. Means comparison

The null (H_0) and alternate (H_1) hypotheses statements established for their evaluation are included in Table 5, which assess the contribution of each BW step to the TMP reduction. A conventional analysis of variance is done in order to do a means comparison against a significance level of 0.05. To illustrate these tests, the first null hypothesis indicates the first step, which is the air scour with or without D does not statistically influence in cleaning the membranes. On the contrary, the alternate hypothesis indicates that the air scour with or without D does statistically influence in cleaning the membranes

2.5. Validation

Once all the hypotheses are contrasted against their confidence interval to assess their statistical significance, an optimum is achieved which reflects the new ideal operating conditions. The last step before implementing the new optimum as a standard is to validate this optimum in a real installation. For this purpose, two ultrafiltration lines are operated in parallel. The first one operates with the standard conditions and the second one operates with the optimum conditions.

This validation is done using brand new DOW™ Ultrafiltration SFP-2660 membranes operating at fluxes more similar to real operating conditions, this means operating at a constant flux of 70 l/m^2 h, with a BW every 30 min, a CEB every 24 h consisting of 6 min of soaking with 350 ppm of NaOCl.

Before doing this validation, a first seven days period operating both lines at the same baseline conditions depicted in Table 6 is performed in order to assess if there are differences between both brand

Table 4
Hypothesis statements to contrast variances

Backwash step	Hypothesis type	Hypothesis statement
AS/D	H_0	The variance of each level of the AS/D variable remains constant
	H_1	The variance of each level of the AS/D variable is different
BWT	H_0	The variance of each level of the BWT variable remains constant
	H_1	The variance of each level of the BWT variable is different
BWB	H_0	The variance of each level of the BWB variable remains constant
	H_1	The variance of each level of the BWB variable is different
FF	H_0	The variance of each level of the FF variable remains constant
	H_1	The variance of each level of the FF variable is different

Table 5
Hypothesis statements to contrast means

Backwash step	Hypothesis	Hypothesis statement
AS/D	H_0	The AS/D step does not influence significantly the fouling decrease
	H_1	The AS/D step does influence significantly the fouling decrease
BWT	H_0	The BWT step does not influence significantly the fouling decrease
	H_1	The BWT step does influence significantly the fouling decrease
BWB	H_0	The BWB step does not influence significantly the fouling decrease
	H_1	The BWB step does influence significantly the fouling decrease
FF	H_0	The FF step does not influence significantly the fouling decrease
	H_1	The FF step does influence significantly the fouling decrease

Table 6
Baseline conditions

Parameter	AS	D	BWT + AS	BWB	FF
Time (s)	30	30	30	30	30
Flux ($l/m^2 h$)	–	–	80	80	80
Flow air (m^3/h)	12	–	12	–	–

Table 7
Optimum conditions

Parameter	AS	D	BWT + AS	BWB	FF
Time (s)	–	–	30	–	30
Flux ($l/m^2 h$)	–	–	80	–	80
Flow air (m^3/h)	–	–	12	–	–

new modules or if there are differences between both ultrafiltration lines.

After assessing there are no differences in both ultrafiltration modules and both lines, a second 25-days period is performed. Therefore, the first line operates at the baseline conditions depicted in Table 6, while the second line operates at the optimum conditions depicted in Table 7. The optimum is validated if during this period both lines do not show major differences and show the same sustainable operating trend.

3. Results and discussion

3.1. TMP increase and efficiency

After all the experiments are completed, the TMP increase and the theoretical efficiency are calculated according to Eqs. (1) and (4), respectively. To illustrate the assessment and calculation of the experimentally obtained TMP increase, Fig. 3 depicts the TMP evolution over time of two experiments. The first experiment (0 0 0 0) where no cleanings are done show a straight line representing the constant TMP increase, while the second experiment (1 1 0 0) where only an air scour and a BWT are done show a straight line that every 30 min is being interrupted by a cleaning which reduces the TMP when performed.

All these results are summarized in Table 8, where the results are stored putting the experiments showing a higher efficiency first. The ultimate goal is to minimize the TMP increase while maximizing the efficiency.

These points are plotted in Fig. 4 where the increase in TMP is a function of the efficiency. Therefore, the optimum point is the one allocated at the BWB right part of the plot and seeks a compromise between the starting point, represented by

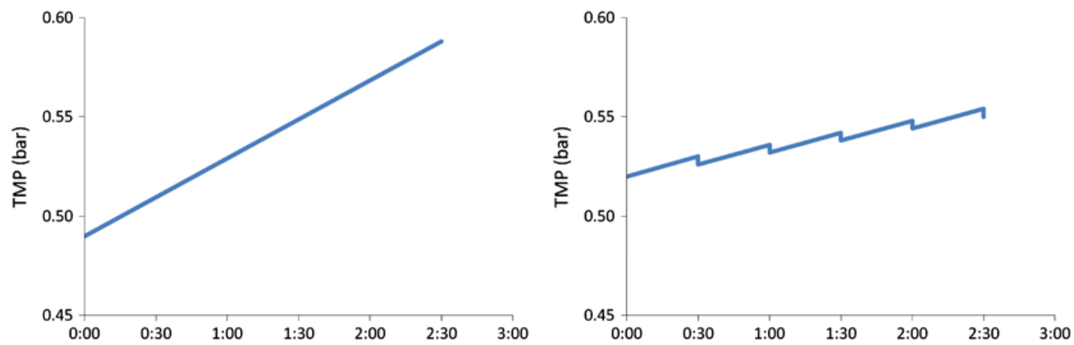

Fig. 3. Evolution of normalized TMP with and without BWs.

Table 8
Efficiency and TMP increase of each experiment. Results ordered by efficiency

Exp	AS/D	BWT	BWB	FF	Efficiency (%)	TMP increase (%)
1	0	0	0	0	100.00	20.72
24	0	2	0	0	97.04	8.03
25	0	2	0	0	97.04	9.68
28	1	0	0	1	96.04	7.02
9	1	0	0	1	96.04	7.73
7	2	0	0	1	95.53	5.07
26	2	0	0	1	95.53	5.67
21	1	1	0	0	95.37	3.91
2	1	1	0	0	95.37	4.65
23	1	0	1	0	95.37	13.50
13	1	0	1	0	95.37	24.15
3	2	2	0	0	94.86	4.49
22	0	2	0	1	94.85	2.78
15	0	0	1	1	94.85	7.48
4	0	1	0	1	94.85	13.01
12	0	2	1	0	94.16	10.63
20	2	0	1	1	92.74	2.20
11	2	1	0	1	92.74	7.32
14	2	1	1	0	92.06	6.44
18	0	1	1	1	92.05	1.89
19	1	2	1	1	90.50	1.57
16	1	1	1	1	90.50	6.76
5	1	1	1	1	90.50	6.83
10	1	1	1	1	90.50	10.04
17	2	2	1	1	90.02	2.31

experiment 17 (2 2 1 1) where all the BW steps are performed and has the lowest TMP increase but lowest efficiency, and the most unfavorable point, represented by experiment 1 (0 0 0 0), where no cleanings are done and has the highest efficiency with the highest increase in TMP.

Fig. 4 suggests experiment 22 (0 2 0 1), where a BW consist only the two steps sequence of a BWT with an air scour and a FF as the optimum experiment which maximizes the efficiency while keeps the TMP increase at the same level as the starting point. Table 9 summarizes the efficiency and TMP increase achieved for the starting point, the no cleanings point, and the optimal point, which shows a TMP increase from 2.31 to 2.78% and efficiency increase from 90.02 to 94.85%.

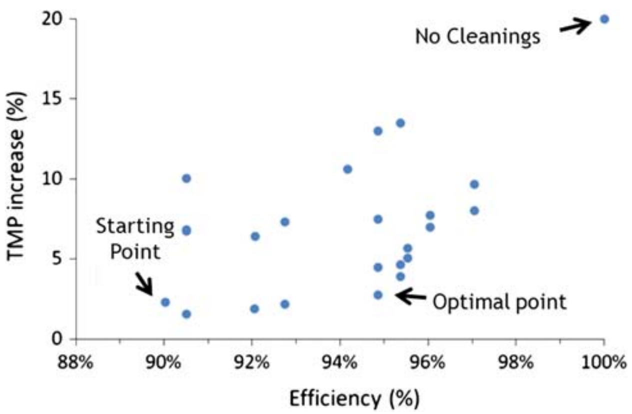

Fig. 4. TMP increase vs. efficiency of each experiment.

3.2. Hypothesis testing

To validate the optimum BW sequence identified, a formal statistical hypotheses contrast analysis is done. The null hypothesis states the specific BW step does not statistically contribute the TMP reduction, while the alternate hypothesis states the specific BW step does statistically contribute the TMP reduction. This allows to determine which backwash steps are statistical significant and therefore, contribute the less to the TMP increase.

3.2.1. Variances comparison

Table 10 summarizes the results obtained from each hypothesis contrast. As the *p*-values obtained are bigger than the significance level of 0.05, the null hypothesis cannot be rejected, which means there are no differences between variances.

3.2.2. Means comparison

Table 11 summarizes the results obtained from the hypotheses comparison. It can be observed that the BWB step is not statistically significant at all. The AS/D, the D and the BWT step are also not statistically significant, although the BWT step shows a slightly statistical significance. Finally, the FF step is statistically significant. These hypotheses contrast can be visually assessed in Fig. 5.

Table 9
Comparison between the starting conditions and the optimal conditions

Experiment	AS/D	BWT	BWB	FF	Efficiency (%)	TMP increase (%)	Description
1	0	0	0	0	100.00	20.72	No cleanings point
22	0	2	0	1	94.85	2.78	Optimal point
17	2	2	1	1	90.02	2.31	Starting point

Table 10
Results of variances comparison

Backwash Step	*p*-value	Hypothesis validated	
AS/D	0.3390	H_0	The variance of each level of the AS/D discrete variable remains constant
BWT	0.3158	H_0	The variance of each level of the BWT discrete variable remains constant
BWB	0.4794	H_0	The variance of each level of the BWB discrete variable remains constant
FF	0.0791	H_0	The variance of each level of the FF discrete variable remains constant

Table 11
Results of means comparison

Backwash Step	*p*-value	Hypothesis validated	
AS/D	0.2416	H_0	The AS/D step does not influence significantly the fouling decrease
BWT	0.1852	H_0	The BWT step does not influence significantly the fouling decrease
BWB	0.9593	H_0	The BWB step does not influence significantly the fouling decrease
FF	0.0299	H_1	The FF step does influence significantly the fouling decrease

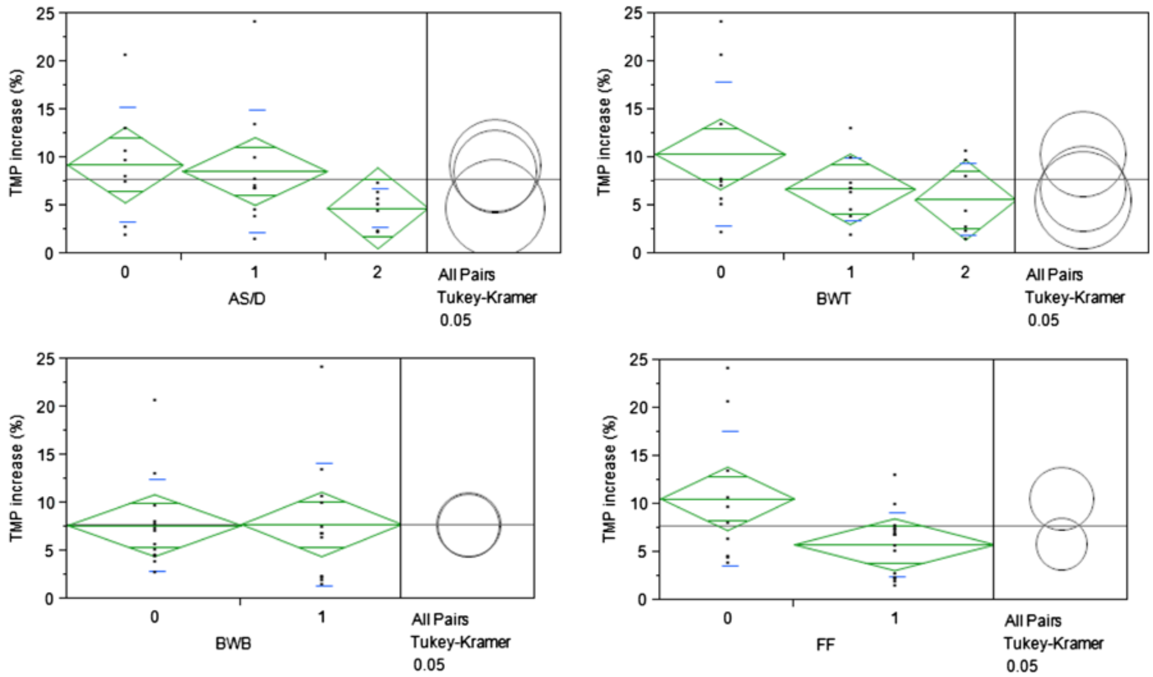

Fig. 5. Variances and means comparison of the ANOVA results.

3.2.3. Model fit

In order to determine if the air scour and the BWT steps have some statistical influence in reducing the TMP, a model is constructed. This model only takes into account the primary factors as the data are obtained from a fractional design of experiments. The model is based on a first-grade polynomial fit as it follows the Taylor series approach that states that for a given range, any complex equation can be fit within an "n" grade polynomial.

Fig. 6 shows the experimentally obtained TMP increase vs. the model predicted TMP increase of each experiment and it presents a determination coefficient (r^2) of 0.5094 and an adjusted coefficient (r^2 adjusted) of 0.3459. The model is statistically significant as the p-value obtained is 0.0284 and there is no statistically lack of fit as the p-value obtained is 0.0909.

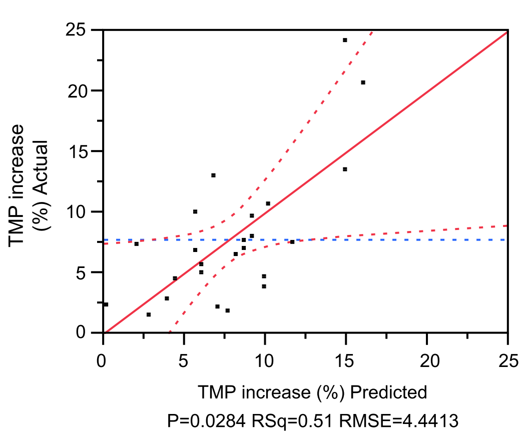

Fig. 6. Experimentally obtained TMP increase vs. predicted TMP increase.

Table 12 summarizes the BW steps that are statistically significant according to the model prediction. Therefore, it can be assessed the air scour and the BWB steps are not statistically significant, while the BWT and the FF steps are statistically significant since the p-value is smaller than the confidence level of 0.05.

Table 13 summarizes the statistically significance of each value each BW step can have. Therefore, it can be seen not doing the BWT (BWT[0]) step is statistically negatively significant, while doing it with an air scour (BWT[2]) is statistically positively significant. Moreover, not doing the forward flush (FF[0]) is statistically negatively significant while doing it (FF[1]) is statistically positively significant since the p-value is smaller than the confidence value of 0.05.

3.2.4. Model boundaries

To determine when these conclusions extracted are valid, the model boundaries are determined. Therefore, a hypotheses contrast against a significance level of 0.05 is made in order to determine if the average feed turbidity, the average feed temperature, and the feed pressure statistically influences the TMP increase. Table 14 shows the fittings of these three variables. From the evaluation of the determination coefficients

Table 12
Main effects analysis

Backwash Step	*p*-value	Hypothesis validated	
AS/D	0.1619	H_0	The AS/D step does not influence significantly the fouling decrease
BWT	0.0288	H_0	The BWT step does influence significantly the fouling decrease
BWB	0.6082	H_0	The BWB step does not influence significantly the fouling decrease
FF	0.0129	H_1	The FF step does influence significantly the fouling decrease

Table 13
Backwash steps statistically significance

Term	Coefficient	*p*-value	Result
Intercept	7.92694	<.0001	Statistically significant
AS/D[0]	2.273701	0.1124	Not statistically significant
AS/D[1]	0.194669	0.8838	Not statistically significant
AS/D[2]	−2.46837	0.0834	Not statistically significant
BWT[0]	3.62437	0.0106	Statistically significant
BWT[1]	−0.41149	0.7546	Not statistically significant
BWT[2]	−3.21289	0.0405	Statistically significant
BWB[0]	−0.47923	0.6082	Not statistically significant
BWB[1]	0.479229	0.6082	Not statistically significant
FF[0]	2.61731	0.0129	Statistically Significant
FF[1]	−2.61731	0.0129	Statistically significant

Table 14
Fittings of the average turbidity, average temperature and initial feed pressure

Variable	Abbreviation	R^2	*p*-value	Result
Turbidity (NTU)	TB	0.000544	0.9119	Not statistically significant
Temperature (°C)	T	0.021228	0.4871	Not statistically significant
Pressure feed (bar)	P_0	0.045779	0.3044	Not statistically significant

and the analyses of variance it can be seen the three models fit poorly and they are not statistically significant. Therefore, the conclusions extracted from this research are valid at least for seawater with a feed turbidity between 0 and 3 NTU, for a temperature ranging from 20 up to 30°C and for a feed pressure ranging from 0.6 to 1.0 bar. Fig. 7 shows the different plots for the TMP increase vs. the average turbidity, the average temperature, and feed pressure of each experiment with their correlations.

3.3. Validation

Fig. 8 shows the first operating period where both lines run at the exactly same operating conditions with brand new modules. From this graph, it can be seen that there are no major differences between both modules and both lines, as they show the same fouling trend and the same stable operation.

Fig. 9 shows the baseline conditions maintained during the first seven days of operation against the new optimum conditions extracted from the DOE experiments. From this plot, it can be seen that both lines show the same fouling trend for these 25 days of operation. Therefore, it can be concluded the optimum conditions are validated.

4. Conclusions

The BW cleaning process is simplified from 5 to 2 steps showing a reduction of 60% in the number of steps and this improvement is validated through statistics using different hypotheses statements contrast. This is achieved by eliminating the redundant steps involved, the time the valves take to change their states and the time needed for the backwash pump to ramp up and down to their set point in each step.

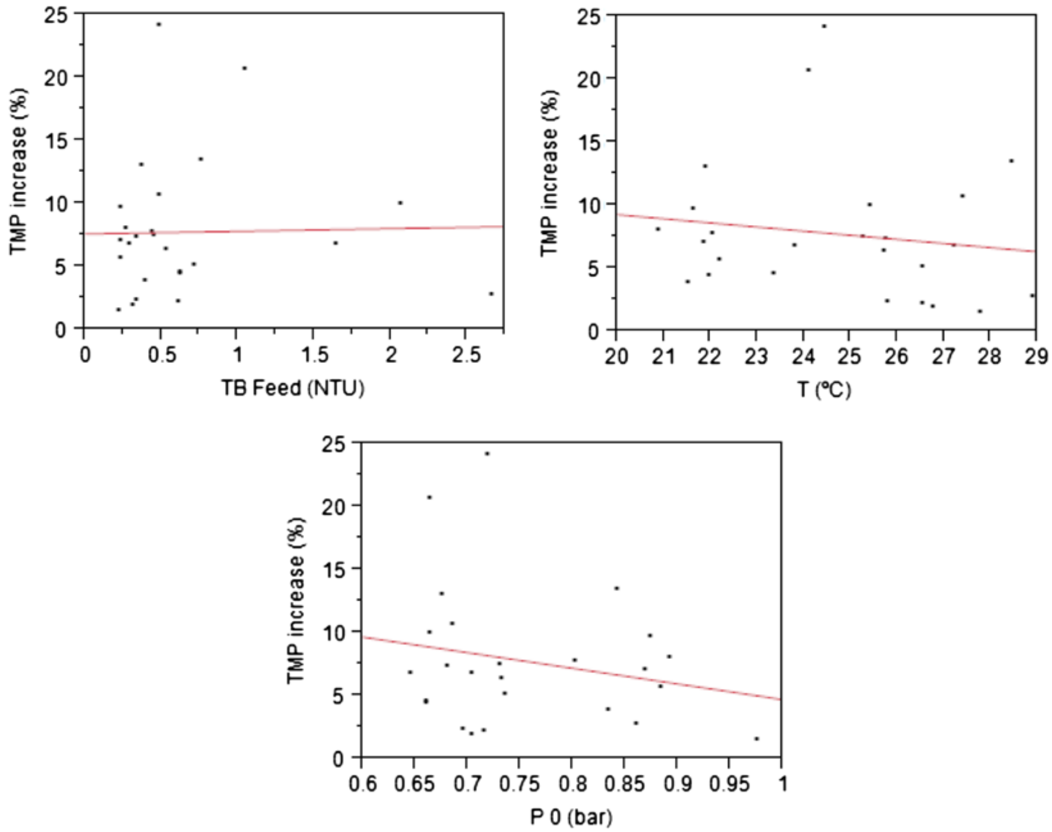

Fig. 7. Effect of feed turbidity, temperature and feed pressure on TMP increase.

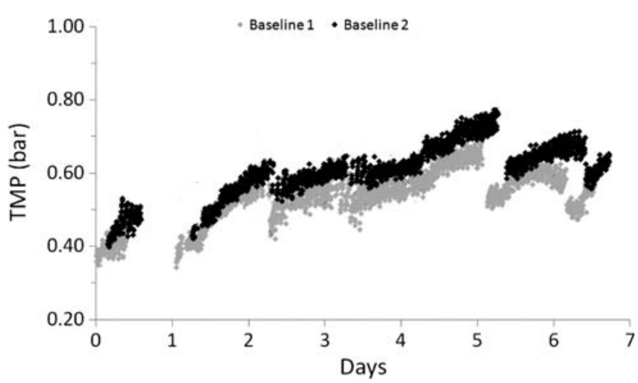

Fig. 8. Baseline conditions in both ultrafiltration lines.

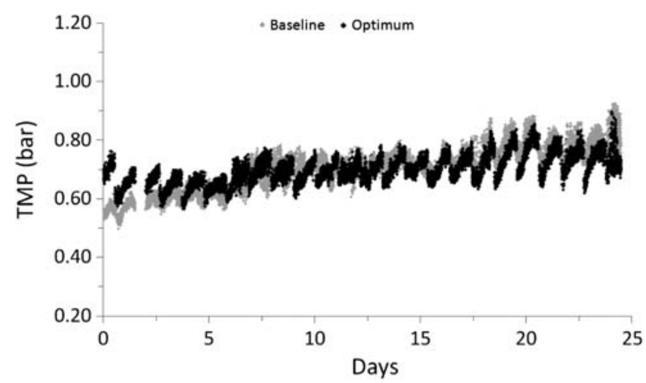

Fig. 9. Baseline conditions against optimum conditions.

These conclusions are proven statistically valid for seawater with a turbidity ranging from 0 to 3 NTU, from a temperature ranging from 20 to 30˚C and from a feed pressure ranging from 0.6 to 1.0 bar and are validated through 25 days of stable operation.

In the past, DOW™ Ultrafiltration membranes were used in Qingdao 2009 with an efficiency of 80% as some other commercially available ultrafiltration systems show nowadays [12]. After the first improvement phase done in Barcelona, the efficiency of DOW™ Ultrafiltration was increased up to 90% [12]. Nowadays, and thanks to this research, DOW™ Ultrafiltration technology has experienced an efficiency increase up to 95%. This means an increase in efficiency of 20% and a decrease in inefficiency of 75% compared with some solutions currently available in the market.

A better understanding of the ultrafiltration process is also achieved as some duplicities are identified. Therefore, the aeration effect done by the air scour

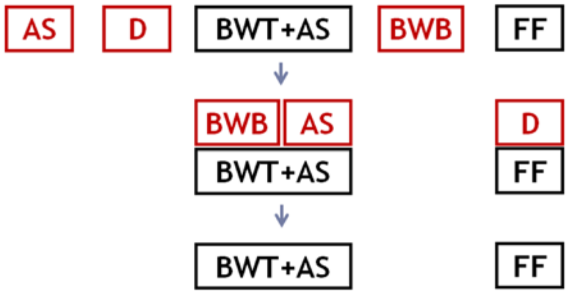

Fig. 10. Lean Six Sigma waste reduction approach used to understand the improvement process.

step is already included in the BWT with air scour step. The function of the D step is to empty the module which contains dirty water coming out from the cleaning of the previous step. However, the forward flush step already achieves this effect because it fills the module with fresh water that displaces the dirty water; and it does in addition, a shearing effect above the fibers that prevents the dirty water to get stuck above the fibers while the module is being emptied. The function of the BWB step is to do a BW using the already filtrated water do unblock the fiber blocks. However, the BWT with air scour steps already achieves this effect as it is not deemed important if the dirty water coming out from the fibers goes out from the module by the top concentrate valve or the bottom feed valve. Fig. 10 describes this logic using a path diagram and following a Lean Six Sigma waste reduction approach.

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