Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2016.11144

61 (2017) 222–229
January

Alternative cleaning method for ultrafiltration membrane system

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Received 3 April 2015; Accepted 18 July 2016

ABSTRACT

Ultrafiltration membranes may face fouling problems if a proper cleaning strategy is not used. Therefore, a good cleaning strategy may help to maintain sustainable operation which will be reflected in constant flux production and no increase on transmembrane pressure. Typical cleaning combine mechanical cleaning strategies (backwash (BW), air scour (AS) and forward flush (FF)) and chemical cleanings (chemically enhanced backwash (CEB)) at regular intervals. This is sometimes followed by a more aggressive chemical cleaning which consist of cleaning in place (CIP) done at longer intervals. The current report describes an alternative cleaning strategy which consist of the complete elimination of CEBs and use of short CIPs at higher frequency in order to reduce filtrate water consumption and increase UF availability. First trial was performed at "The Dow Water and Process Solution Global Water Technology Center" in Tarragona, Spain and used Mediterranean sea water as feed. The second trial used waste water from urban waste water treatment plant in Vilaseca, Spain. Both trials showed that with the alternative cleaning protocol, DOW™ UF can maintain stable and sustainable operation over a long period of time. A comparative study with UFlow Dow Software was done simulating a large scale facility of 100 UF modules in order to understand the benefit of alternative cleaning effect on large scale in terms of availability, recovery, efficiency and water consumption. Further evaluation indicated the following benefits of the alternative cleaning protocol compared to standard cleaning protocol: Around 9% higher total efficiency of the UF system; Approximately 5% higher net production of UF filtrate; Lower chlorination risk in reverse osmosis integrated systems as no chemical enhanced backwash is done; No ultrafiltration waste water generated, as no CEB is done.

Keywords: Alternative cleaning; Cleaning improvement; Chemical enhancement; Sea water; Ultrafiltration; Waste water

1. Introduction

Ultrafiltration (UF) is used in multiple types of water sources to remove virtually all suspended matter and also dissolved organic compounds depending on their molecular weight and on the molecular weight cut-off of the membrane [1]. Fouling is considered one of the major problems in UF causing a decrease in treated water production as well as increase of transmembrane pressure (feed pressure–filtrate pressure) [2]. Most researchers in this area mention fouling as a bottleneck to sustainable UF operation. Vrouwenvelder [3] listed the consequences of fouling in a membrane system which are 1) increase of operational feed pressure and energy need, 2) increase of cleaning frequency and 3) decrease of membrane lifetime. In order to combat fouling, Lee (2001) mentions different strategies such as better pre-treatment, membrane surface modifications, decrease of operation conditions (i.e., flux) and better cleaning of the membranes [4]. Nonetheless, they still suggest that efficient membrane cleaning is highly recommendable for a sustainable UF operation. The UF cleanings may increase membrane life, avoiding irreversible fouling and irreparable damage.

Even though cleaning strategies may vary depending on feed water source, foulant, membrane material or plant

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Presented at EuroMed 2015: Desalination for Clean Water and Energy Palermo, Italy, 10–14 May 2015. Organized by the European Desalination Society.

configuration, most researches indicate that combination of mechanical and chemical cleaning is normally used to efficiently clean the membrane. Mechanical cleaning normally includes backwashes, air scour and forward flush while chemical cleaning generally used are chemically enhanced backwash and clean in place. According to Paul Chen et al., cleaning efficiency will depend on many parameters such as hydrodynamic conditions, concentration and temperature of chemical solution and sequence of cleaning [5]. Therefore, following a standard cleaning strategy may not be optimal solution for all ultrafiltration systems, having high flexibility to optimize the different cleaning parameters.

Optimization of cleaning parameters such as water consumption, chemical dosage and duration time are key factors for increasing successfully the UF recovery, efficiency and availability. Objective of this research is to test an alternative cleaning protocol which increases the above factors while maintaining constant flux and transmembrane pressure. It is seen that there is a need of a new cleaning strategy for two different water treatment applications. On one side, it is detected that current standard UF cleaning protocol is not convenient for offshore applications where UF technology may be used for pre-treatment of sulphate removal units. For this application, in order to optimize footprint, it is required to reduce the filtrate water used in cleanings, thus eliminating the filtrate tank. Another objective of this application is to increase the UF system availability and also to reduce chemical storage. On the other side, for some water reuse applications it is detected that standard cleaning is not efficient to keep sustainable operation of UF due to the reaction of sodium hypochlorite with high ammonia concentration in the feed water. Thus, there is a need to increase the efficiency of the standard cleaning, increase the ultrafiltration system availability and reduce the chlorination risk when working with RO integrated systems.

Alternative cleaning tends to eliminate UF filtrate consumption during backwashes and chemical enhanced backwashes, incorporating only clean in place performed in shorter duration of 30 min and with higher frequency than standard CIP. This cleaning process explained in this paper is an optimization of standard cleaning protocol based on the reduction of filtrate water wastage, time and chemicals.

2. Design of experiment

2.1. Cleaning protocol

The cleaning protocol involves hydraulic and chemical cleanings. Hydraulic cleaning includes only air scour and forward flush thus eliminating backwashes with UF filtrate. The purpose of elimination of backwashes is to decrease filtrate water wastage during cleanings. Chemically enhanced backwashes are not performed in a daily basis although recommended by most of the ultrafiltration manufacturers and researchers. Instead of CEB, a 30 min CIP is done. The shorter CIP is performed in higher frequency of once or twice per week compared to Standard CIP done once every two to three months for a longer duration of 2–4 h. Chemical concentration used in the short CIP does not vary from the recommended standard CIP. Table 1 shows an example of standard cleaning compared with alternative cleaning developed in this study.

The details of the short CIP are described below:

- **Step 1:** Preparation of the solution in the dedicated CIP tank. The solution concentration is 2000 mg l^{-1} sodium hypochlorite at a temperature of 35ºC. However, acid solution may be required depending on the type of foulant. Prior to the short CIP a flux test, a backwash or a flushing can be done depending on the fouling intensity.
- **Step 2:** Solution recirculation through the module for 10 min.
- **Step 3:** Soaking for 10 min which includes air scour for 30 s for every 2 min.
- **Step 4:** Recirculation of solution through the module for 10 min.
- **Step 5:** Forward flush with feed water for 5 min may be needed before starting the UF filtration to prevent possible membrane chlorination in RO located downstream. The duration of this step may depend on the system design (i.e. pipe length and elbows). This step may be avoided if UF is not part of an integrated RO system.

2.2. Pilot plant set-up

Two different trials performed to test the efficiency of alternative cleanings. In trial 1, sea water was used as feed while trial 2 was done using waste water. Both tests were done using vertically pressurized UF module made with PVDF hollow fibers of nominal pore diameter of 0.03 µm. The details of the test are explained below:

- **Trial 1** was conducted at the Global Water Technology Center (GWTC) in Tarragona, Spain using sea water

Table 1
Example of standard UF cleaning compared with alternative cleaning

Standard cleaning	Alternative cleaning
Air scour	Air scour
Backwash top	Forward flush
Backwash bottom	
Forward flush	
Frequency: 20–90 min	Frequency: 60 min
Duration: 6–10 min	Duration: 5 min
Chemically enhanced backwash	Chemical enhanced backwash
Frequency: 8–24 h	Not performed
Duration: 25–30 min	
Chemical: i.e. 350 mg l^{-1} sodium hypochlorite	
Cleaning in place	Cleaning in place
Frequency: 1–3 mo	Frequency: 1–2 per week
Duration: 2–4 h	Duration: 30 min
Chemical: i.e. 2000 mg l^{-1} sodium hypochlorite Temperature: 30–40ºC	Chemical: i.e. 2000 mg l^{-1} sodium hypochlorite Temperature: 30–40ºC

from Mediterranean Sea as feed. Ultrafiltration was working as pre-treatment to a reverse osmosis system which is located downstream. UF module used was commercial Dow™ SFP-2880 module with surface area of 77 m^2. It consists of hydrophilic PVDF fibers with outside-in configuration and have nominal pore size of 0.03 µm. The filtrate produced was stored in filtrate tank in order to have water available for cleanings. The pilot plant has also a RO permeate water tank with heater available for CIP cleanings. Fig. 1 shows the pilot plant arrangement.

- **Trial 2:** Pilot plant is located in urban WWTP in Vila-seca, Spain. UF module installed was commercial Dow™ UFIW-102 with surface area of 102 m^2 made of hydrophilic PVDF fibers with outside-in technology and nominal pore size of 0.03 µm. UF feed was coming from secondary water treatment of the WWTP with water from filtrate and clean in place tank available for UF cleaning. The UF downstream feed the first stage and the second stage of a reverse osmosis system located downstream.

In order to take the effect of the temperature when assessing the evolution of the parameters typically used to monitor the performance of an UF system, i.e., TMP and permeability, normalization equations are used [Eqs. (1)–(3)]. The TMP is the difference between feed pressure and filtrate pressure, while the water permeability is defined as the ratio between the operational flux (flow/filtration area) and the TMP. In order to normalize both TMP and permeability to take into account the temperature effect, it is needed to calculate the temperature correction factor (TCF). The TCF formula takes into account the liquid water viscosity at different temperatures. The formula used is given by

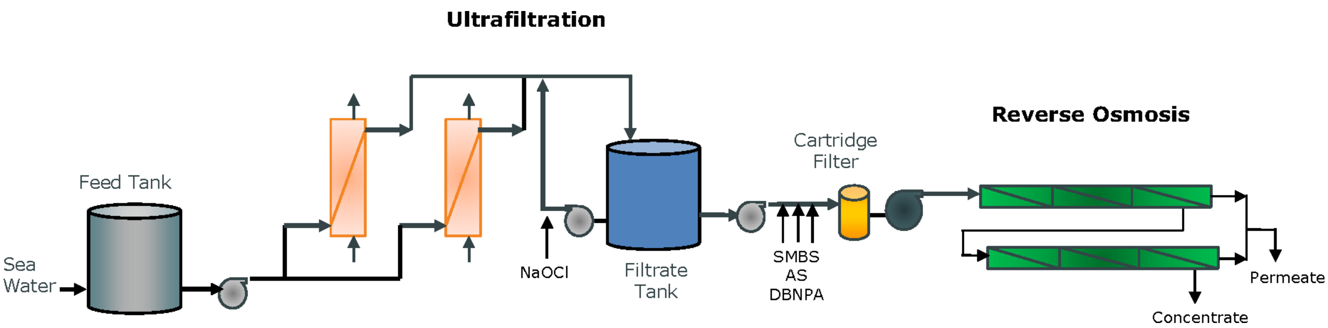


Fig. 1. Seawater pilot scheme used in Trial 1.

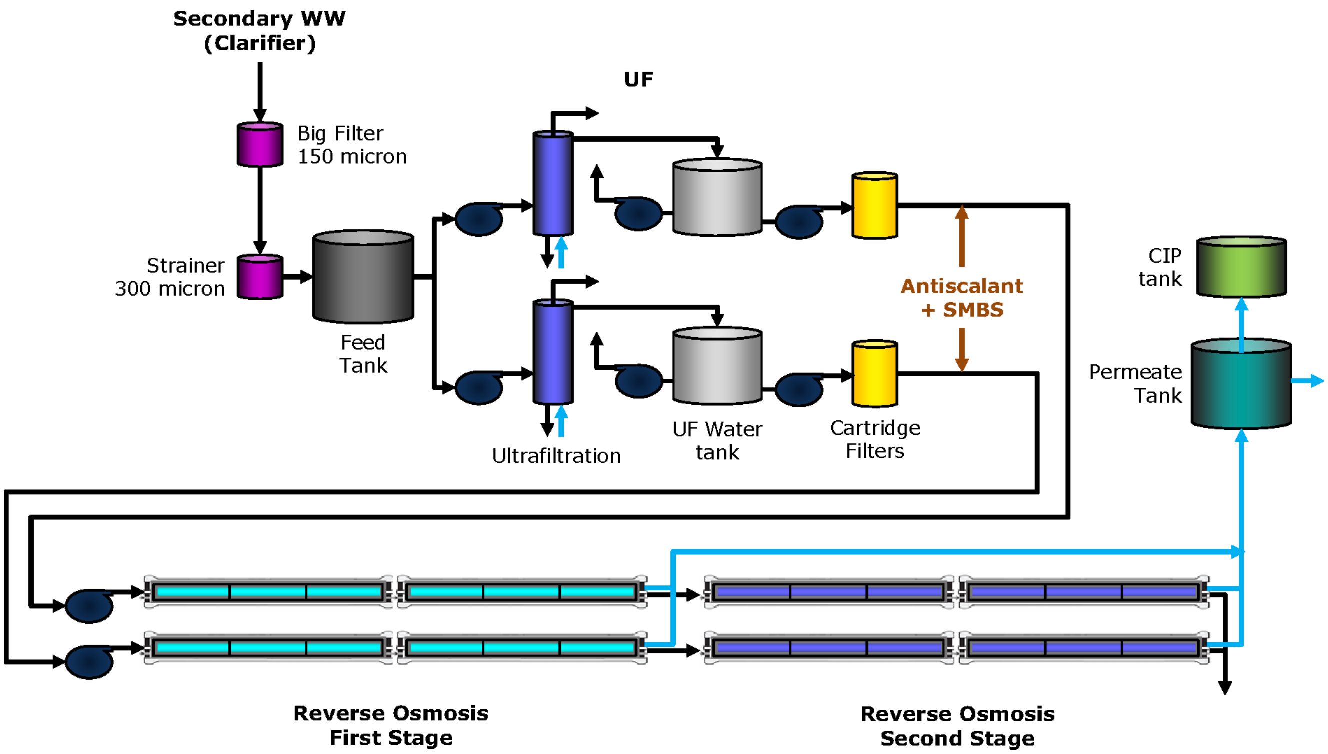


Fig. 2. Waste water pilot scheme used in Trial 2.

the International Association for the properties of water and steam (IAPWS) for liquid water between 253.15 K to 383.15 K [6] [Eq. (1)]. T_K in Eq. (1) corresponds to temperature in Kelvin degree. The TCF factor is multiplied by the raw TMP in order to get the normalized TMP. In the present report, only TMP was monitored for the UF operation using the alternative cleaning protocol.

$$TCF = \frac{890}{\left(280,68\cdot\left(\frac{T_K}{300}\right)^{-1,9}\right)+\left(511,45\cdot\left(\frac{T_K}{300}\right)^{-7,7}\right)+\left(61,131\cdot\left(\frac{T_K}{300}\right)^{-19,6}\right)+\left(0,45903\cdot\left(\frac{T_K}{300}\right)^{-40}\right)} \quad (1)$$

$$\text{Normalized TMP (bar)} = \text{Actual TMP} \cdot \text{TCF} \quad (2)$$

$$\text{Normalized Permeability}\left(\frac{L}{m^2\ hbar}\right) = \frac{\text{Actual Permeability}}{\text{Normalized TMP}} \quad (3)$$

2.3. Cleaning efficiency

Cleaning efficiency was calculated for both trials in order to closely understand alternative cleaning performance. Three different TMPs are considered:

- TMP_i: initial transmembrane pressure which is the clean membrane TMP from previous cleaning. It is the initial TMP value that ideally should be recovered after each cleaning.
- TMP_0: TMP just before a cleaning.
- TMP_f: TMP just after a cleaning.

If TMP_f is higher than TMP_i, cleaning has not been efficient to recover previous TMP values. Therefore, if the efficiency is calculated using Eq. (4), negative values will indicate poor cleaning efficiency meanwhile positive values indicates higher efficiency. Fig. 3 shows an example of TMP_i, TMP_0 and TMP_f. This equation will indicate if irreversible fouling is present, understand as the fouling which cannot be removed by chemical cleanings.

$$\text{Cleaning efficiency} = (TMP_i - TMP_f)/TMP_i \quad (4)$$

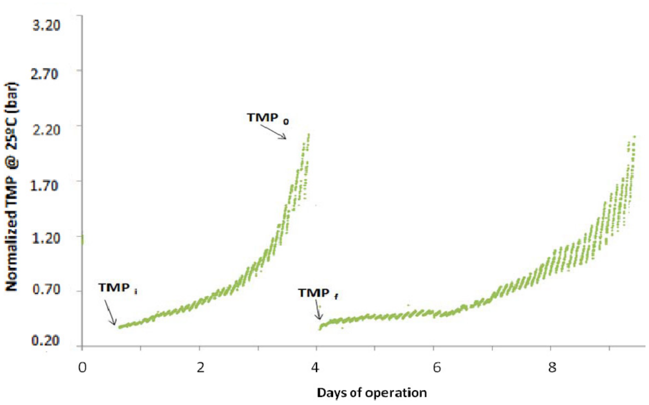


Fig. 3. Trial 1 normalized UF TMP and flux.

2.4. Simulation of standard cleaning vs. alternative cleaning

A comparative study has been done simulating a facility of 100 modules DOW™ SEP-2880 at 80 l m^{-2} h^{-1} working with seawater in order to understand availability, recovery, efficiency and chemical and water consumptions. The simulation is done using Dow internal software called UFlow. The recovery, availability and efficiency have been calculated as indicated in Eqs. (5)–(7). Table 2 shows the operation condition of standard cleaning and alternative cleaning. Based on experimental data obtained during seawater trial, the alternative cleaning frequency is set up every 5 d in the simulation.

For both simulations, recovery, availability and efficiency have been calculated in order to understand how the alternative cleaning protocol is performing in terms of various operational metrics.

The recovery is calculated as the total filtrate net water produced less the filtrate used during the cleanings (BW or CEB's):

$$\text{Recovery}(\%) = \frac{\text{UF Water Net Production} - \text{UF Water}_{BW} - \text{UF Water}_{CEB}}{\text{UF FeedWater}} \cdot 100 \quad (5)$$

The availability is defined as the ratio of the duration of filtration to the total time (filtration time + cleaning time) and is expressed as percentage.

$$\text{Availability}(\%) = \frac{\text{Time}_{Filt}}{\text{Time}_{Total}} \quad (6)$$

Table 2
Cleaning conditions used in the simulation of the standard cleaning vs. alternative cleaning

Parameter	Standard cleaning	Alternative cleaning
Backwash		
Air scour (s)	60	–
Draining (s)	30	
Backwash top (s, l m^{-2} h^{-1})	30, 100	–
Backwash bottom (s, l m^{-2} h^{-1})	30, 100	–
Forward flush (s, l m^{-2} h^{-1})	60, 50	240, 50
Chemical Enhanced Backwash		
Frequency	Every 24 h	–
Dosing chemical (mg l^{-1})	350 NaClO	–
Soaking time (min)	6	–
Clean in Place		
Dosing chemical (mg l^{-1})	2000	2000
Frequency	Every 60 d	Every 5 d
Duration	2 h	30 min

The last parameter studied was the efficiency which is the product of recovery [Eq. (5)] and availability in Eq. (6).

$$\text{Efficiency (\%)} = \text{Recovery} \cdot \text{availability} \quad (7)$$

3. Results and discussion

3.1. Water quality

Ultrafiltration operation strongly depends on the source and quality of the feed water used. Trial with the alternative cleaning protocol was done with two different feed water streams: one using seawater from the Mediterranean Sea and other using waste water from Vilaseca municipal waste water plant (Tarragona).

Typical values for seawater, waste water and filtered water obtained during the trial are shown in Table 3. Although feed water quality varies over the year (high turbidity periods during the year), UF filtrate quality must remain constant.

3.2. Operational data

Process operation parameters were continuously recorded during both trials. Transmembrane pressure normalized at 25ºC and operational fluxes were recorded online for both the pilot plants during the whole operation period.

Trial 1: Fig. 4 shows seawater pilot operation data where alternative cleaning was used for the first time for approximately 1.5 mo. Operational flux was maintained constantly at 80 l m^{-2} h^{-1} when feed temperature was between 20 and 24ºC. Hourly forward flush combined with air scour was useful to decrease the daily TMP. Shorter CIP was normally performed when the normalized TMP increase was above 2 bar. However, as a preventative measure, some of the short CIP were done even though TMP rise was lower. The short CIP are indicated by arrows in Fig. 4. It can be noticed that in the third cleaning, warm water was used at 35ºC without adding any chemical. It was detected that only with temperature, TMP may be partially recovered. Therefore, temperature was considered as a key factor to increase efficiency during this cleaning study.

Trial 2: Fig. 5 shows operational data obtained for more than 130 d of operation at the waste water pilot plant. Operational flux was changed during the experiment, starting with moderate flux of 30 l m^{-2} h^{-1} and increasing in steps of 5 l m^{-2} h^{-1} until it arrived to 60 l m^{-2} h^{-1} operation. The temperature was registered between 19ºC and 27ºC. However, all the data presented in this paper has been previously normalized to 25ºC. Alternative cleanings seems to be efficient not only at moderate fluxes but also at higher fluxes, allowing sustain-

Table 3
Typical feed and filtrate parameters for sea water and waste water

	Sea water		Waste water	
Parameter	Feed	UF Filtrate	Feed	UF Filtrate
Turbidity, NTU	1–20	<0.1	<50	<0.1
TSS, mg l^{-1}	< 15	< 1	<15	<1.5
SDI_{15}	<6	< 2.5	<6	< 2.5
TOC (Shimadzu), mg l^{-1}	0.5–2	0.5–1	5–15	1–12
COD, mg l^{-1} O_2	–	–	10–60	<30
BOD5, mg l^{-1} O_2	–	–	0.5– 5	0.5–5

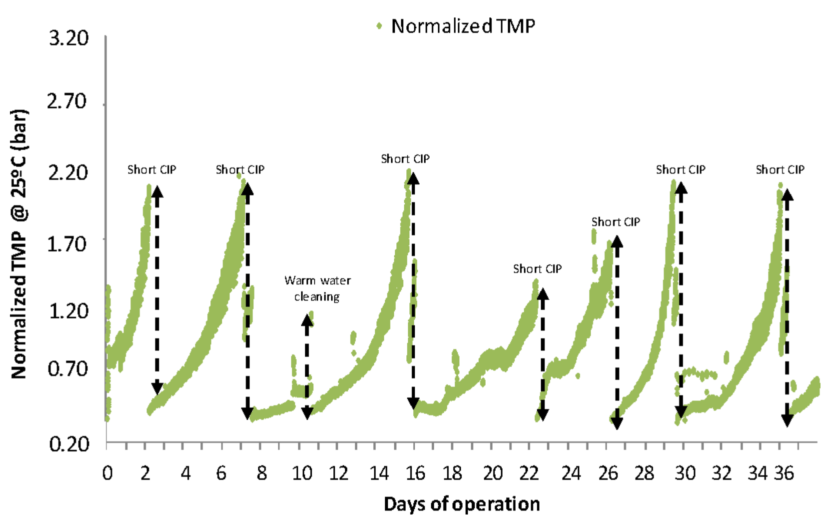


Fig. 4. Normalized TMP results obtained during trial 1.

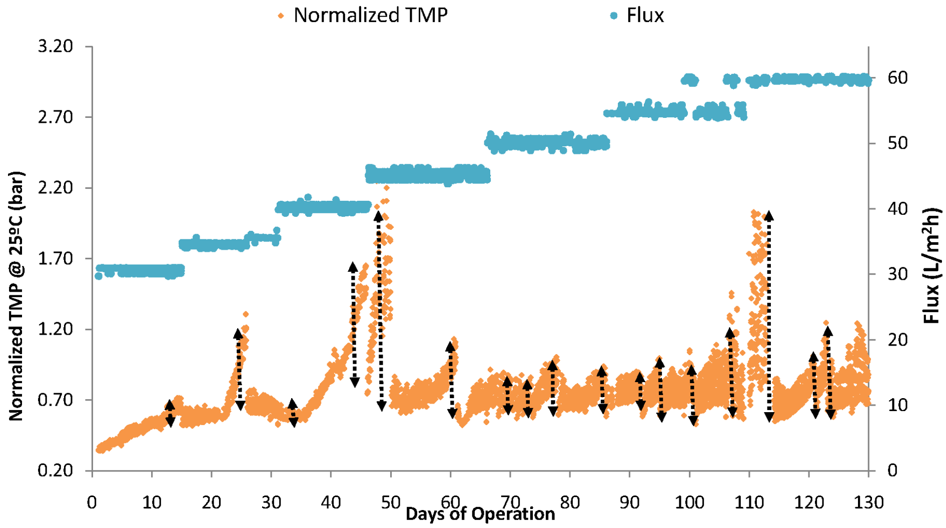


Fig. 5. Normalized TMP and flux monitored during Trial 2.

able operation over the whole period of operation. The short CIP are indicated by arrows as seen in Fig. 5. It can be noticed that during two different periods: period of 40–50 d and period of 105-115 d, TMP was increasing to 2.1 bar. The TMP increase was due to increased turbidity of the feed water.

3.3. Cleaning efficiency

As mentioned in section 2.3, the cleaning efficiency was calculated for both trials following Eq. (4) in order to closely understand alternative cleaning performance. Apart from the cleaning efficiency, three different TMPs are plotted in Figs. 6 and 7:

- TMP_i: initial transmembrane pressure which is the clean membrane TMP from previous cleaning. It is the initial TMP value that ideally should be recovered after each cleaning.
- TMP_0: TMP just before a cleaning.
- TMP_f: TMP just after a cleaning.

Fig. 6 shows three different TMP's and the cleaning efficiency plotted for trial 1 working with seawater. Short CIP was generally recovering to same or lower TMP value compared to initial TMP (TMP_i). Therefore, alternative cleanings helps to maintain constant operation, avoiding extreme irreversible fouling. The cleaning efficiency will strongly depend on the cleaning conditions used in terms of membrane flux, duration and frequency. These parameters were kept constant during the entire experiment as indicated in Table 1 above.

Fig. 7 plots TMP_i, TMP_0, TMP_f for trial 2 using waste water as feed. During more than 130 days, alternative cleaning protocol was effective recovering TMP to initial low values. It can be observed that cleaning efficiency has been maintained at same range during practically all the operation.

3.4. Simulation of standard cleaning vs. alternative cleaning

Fig. 8 and Table 4 show efficiency, availability and recovery results obtained from the simulation. Availability is the difference between the duration of filtration and total time, is around 90% in conventional operation. Using the alterna-

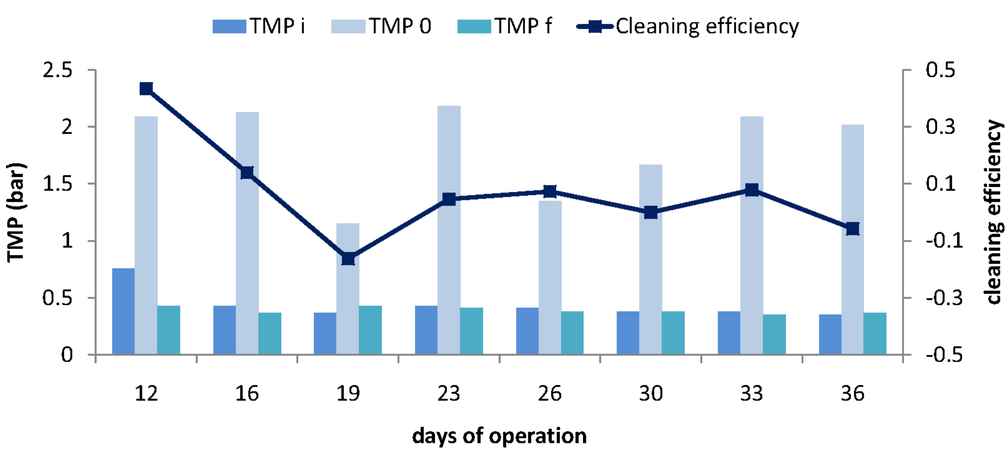


Fig. 6. TMP_i, TMP_0, TMP_f and recovery in trial 1.

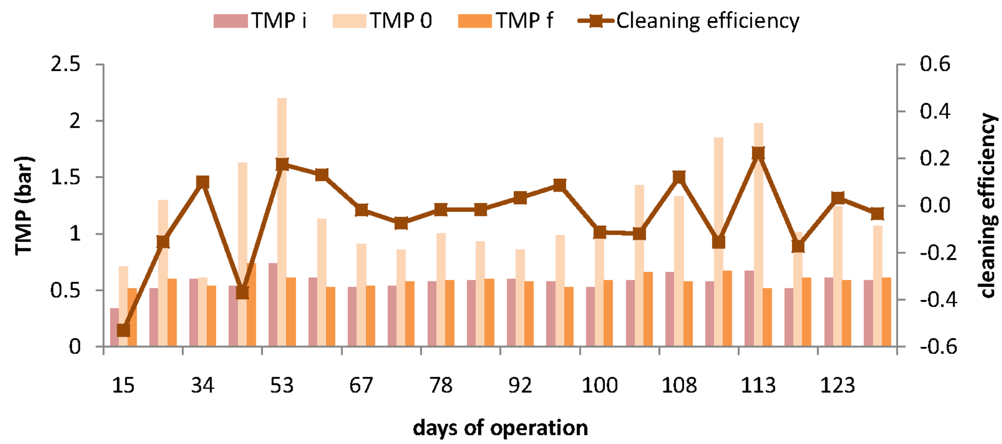


Fig. 7. TMP_i, TMP_0, TMP_f and recovery in trial 2.

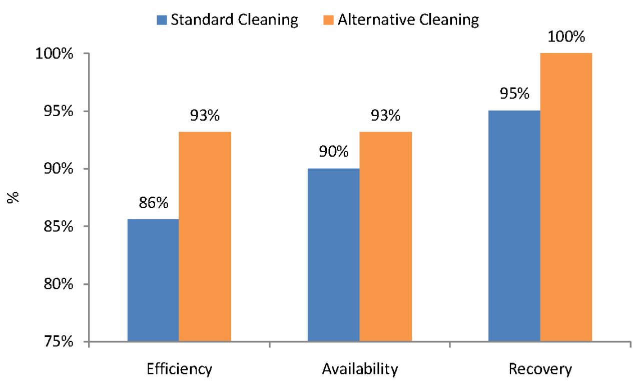


Fig. 8. Efficiency, availability and recovery calculations from the simulation of standard cleaning vs. alternative cleaning.

Table 4
Water consumption and duration of standard cleaning vs. alternative cleaning

Parameter	Standard cleaning	Alternative cleaning
Mechanical cleaning		
Total duration, s	210	240
Total UF filtrate water consumed	13 m^3 per backwash	–
Total feed water consumed	13 m^3 per backwash	66 m^3 per forward flush
Chemical enhanced backwash		
Total duration	20 min per CEB	–
Total UF filtrate water consumed	103 m^3 per CEB	–
Total feed water consumed	77 m^3 per CEB	–
Cleaning in place		
Total duration	2 h per CIP	30 min per CIP
Total RO water consumed	5 m^3 per CIP	1.5 m^3 per CIP

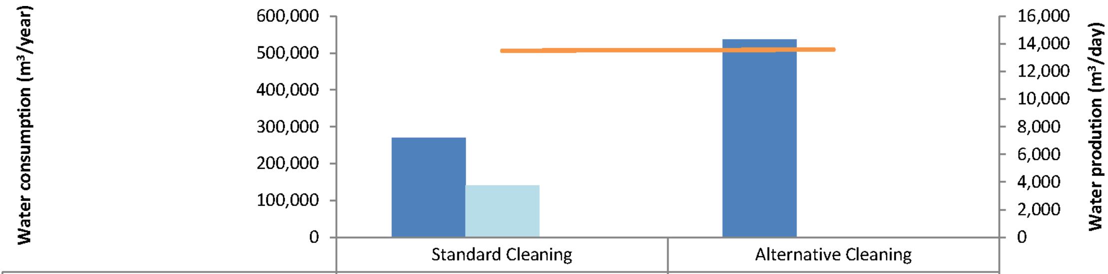
tive cleaning method in seawater conditions, availability has increased by 3% due to reduction in time needed for performing the cleaning sequence. Recovery, expressed as the difference of the total filtrate net water produced and the filtrate used during cleanings (BW or CEB's), is for standard cleaning around 95%. Alternative cleaning protocol show really high recovery of almost 100% as filtrate is not used for cleaning (no CEB is performed and only FF and AS is done as mechanical cleaning). During alternative cleanings, only permeate water from RO is used instead of UF filtrate. However, it must be noted that for an integrated UF + RO system, it is recommended to do a BW to remove chemicals after short CIP, which will slightly decrease total filtrate recovery. The efficiency shows an increase of around 9% when using the alternative cleaning instead of the standard one.

Fig. 9 shows water production and water consumption during one year of estimated operation. Data shows similar range of water production in both cases while producing extra 28,000 m^3 of volume per year when alternative cleanings is used. Time and water savings in cleaning protocol are significantly impacting the yearly production. Standard cleaning consumes three types of waters: feed, UF filtrate and RO permeate; alternative cleaning does not use UF filtrate. Fig. 9 shows higher consumption of total water in alternative cleanings due to forward flush which is much longer than in standard cleaning. However, most of the water consumed in alternative cleanings is feed water (sea water or waste water). Due to higher frequency of CIPs in alternative cleanings, RO permeate consumption is higher than in standard cleanings. However, RO permeate volume needed for alternative cleanings seems affordable.

4. Conclusions

Alternative cleaning protocol has been tested successfully for long period of time for two types of waters: sea water and waste water. The following conclusions can be drawn from the trial:

- Ultrafiltration system shows stable operation (constant flux and low TMP) using alternative cleaning protocol.



	Standard Cleaning	Alternative Cleaning
Total water consumed (m3/year)	270211	537526
Total UF water consumed (m3/year)	139667	0
Total RO water consumed (m3/year)	30	365
Total water produced (m3/day)	13507	13585

Fig. 9. Water production and water consumption calculations from the simulation of standard cleaning vs. alternative cleaning.

- Short CIP seem to be really effective in TMP recovery. Furthermore, temperature is key factor to obtain high TMP recoveries.
- Alternative cleaning protocol present higher UF system efficiency, around 7.5%, higher recovery of 5% and higher system availability of 3% compared to standard cleaning protocol for 100 modules operating at 80 l m^{-2} $h^{-1.}$
- Total UF filtrate net production is higher for alternative cleanings
- UF filtrate water waste is lower, as no CEB's and standard backwashes are used in the alternative cleaning protocol.

Acknowledgments

The authors wish to thank the Global Water Technology Centre of Tarragona, Spain, for providing pilot plant and analytical resources.

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