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A pilot-scale comparison between granular media filtration and low-pressure membrane filtration for seawater pretreatment

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ABSTRACT

This paper summarizes the results of a long-term comparative pilot-scale study on seawater pretreatment for reverse osmosis (RO) desalination. A conventional granular media filtration pretreatment (CPP) and a low-pressure membrane filtration pretreatment (MPP) were operated side-by-side at a site located on the Mediterranean Sea. This study showed that the SDIs after microfiltration were lower than the ones obtained after coagulation + granular filtration: average SDI_{15} was 3.5 at CPP outlet and 2.5 at MPP outlet. Microorganism removal in terms of bacteria and picophytoplankton was also highly better at the MPP outlet (1.8 log vs. 0.6 log for bacteria removal, 4 log vs. 0.8 log for plankton removal). On the other hand, removal of dissolved organic matter was significantly lower for the MPP as compared to the CPP. During this study, a higher fouling potential of the MPP outlet water was demonstrated through the monitoring of RO units fed by the two pretreatment processes. Indeed, while the longitudinal pressure drop was almost stable to 0.1 bar for the two RO membrane units, the normalized permeate flow decreased by 15% for the RO unit fed by CPP outlet water versus more than 30% for the RO membrane fed by MPP outlet water. According to these results, despite that MPP provided lower SDI values than CPP, the fact that it did not retain dissolved organic matter led to a higher extent of organic fouling on the RO membrane fed with the microfiltration pretreatment.

Keywords: SWRO desalination; Seawater characterization; Granular pretreatment; Membrane pretreatment

1. Introduction

RO desalination is an effective process to convert seawater into fresh water for potable use. However, a pretreatment is necessary to ensure that feed water will not cause fouling problems or precipitation at the RO membrane surface. Most of the desalination plants use conventional pretreatment processes (i.e. dual media filtration preceded by coagulation and sometimes by ballasted sedimentation or air flotation for more challenging seawaters). Despite these conventional processes are quite efficient in decreasing the fouling ability of the raw seawater, they nevertheless present some limits, such as a strong dependency on seawater quality variations, a difficulty to maintain a SDI below 3 and to remove particles smaller than 10 µm. Moreover, conventional pretreatment processes often lead to high plant footprint due to low filtration velocities and the use of coagulant, such as ferric salts, implies adequate collection and treatment of the backwater waters.

In drinking water plants from surface or ground water, low-pressure membrane processes such as microfiltration (MF) or ultrafiltration (UF) are used to produce high quality water independently of the raw water quality. Now that the economic impact of such advanced technologies has strongly decreased, they have become cost-competitive with conventional processes for seawater pretreatment.

There have been few studies about seawater RO pretreatment by membrane processes in the past. In 2006,

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Khumar et al. [1] compared MF and UF membranes in pretreatment to determine differences in filtrate quality: 0.1 µm MF and 100 kDa UF membranes showed no difference in term of flux decrease in the RO element, suggesting equal fouling potential of the filtrate. On the contrary, a 20 kDa UF membrane resulted in a reduced flux decline in the RO element, suggesting less membrane fouling. In 2003, Vial et al. [2] implemented 0.1 µm hollow-fibre membranes for the pretreatment of Mediterranean seawater. They observed no influence of turbidity and SDI peaks on permeate turbidity and SDI. Membrane pretreatment provided high quality feedwater to the RO membrane with an SDI consistently below 1.8, allowing operation at high recovery rates reducing total system running cost. In 2004, Pearce et al. [3] used an UF membrane pretreatment at Port Jeddah, Saudi Arabia, as an alternative to its conventional pretreatment facility, which could not meet targeted feedwater quality during algal blooms and storms. The implementation of membrane pretreatment with daily air-enhanced backwashes achieved an average filtrate SDI of 2.2, which corresponded to an SDI improvement of two units compared to the previous conventional pretreatment. Higher RO feed water quality hence resulted in reduced fouling of the RO element by 75%.

Most of these studies about seawater RO pretreatment by membrane processes are based on an evaluation of pretreatment performance through conventional and limited analytical tools such as SDI, turbidity or particle counts. Moreover, few of these studies presented a side-by-side comparison of conventional and membrane pretreatment fed at the same time by the same seawater.

2. Materials and methods

2.1. Analytical tools for seawater characterization

To date, RO membrane manufacturers have put a lot emphasis on the SDI as a surrogate parameter for seawater quality to prevent fouling of RO membranes. Nevertheless, as this measurement is based on the reduction of permeability with time of a seawater sample through a MF membrane, it may not be as relevant to predict fouling potential for RO membranes notably as foulants promoting and organic and biological fouling can pass through the SDI microfiltration filter. That is why this study assessed the performance of each pretreatment through conventional seawater quality parameters but also through other advanced water parameters such as characterization of NOM by Liquid Chromatography or enumeration of picophytoplankton and bacteria through Flow Cytometry.

2.1.1. Characterization of natural organic matter by liquid-chromatography

The LC-OCD system (Liquid Chromatography-Organic Carbon Detection) consists of a size exclusion chromatography column, which separates hydrophilic organic molecules according to their molecular size. The underlying principle is the diffusion of molecules into the resin pores. This means that larger molecules elute first as they can not penetrate the pores very deeply, while smaller molecules take more time to diffuse into the pores and out again. The separated compounds are then detected by two different detectors: a UV detector (absorption at 254 nm) and a Dissolved Organic Carbon (DOC) detector (after inorganic carbon purging). Depending on the size of the molecules, the composition of the organic matter can be obtained. With a bespoke algorithm program, the different peaks can be integrated to evaluate the proportion of each organic fraction. The DOC measurement can be carried out in the by pass mode with a 0.45µm prefiltration of the samples. In this case, the samples go straight through the TOC reactor and analyser [4].

2.1.2. Enumeration of picophytoplankton and bacteria through flow cytometry

Flow cytometry is an individual, qualitative and quantitative characterization technique for particles (cells, bacteria…) in a liquid field. The sample is injected in a measurement chamber by a sheath fluid. The whole

Table 1
Raw seawater quality from May to October 2007.

	Min	Average	Max
T (°C)	14.3	19.5	23.6
Turbidity (NTU)	0.1	0.3	1.3
UV_{254nm} (/m)	0.5	1.0	1.6
TOC (mg/l)	1.0	1.2	1.5
Total Bacteria (/ml)	$3.5.10^5$	$4.3.10^5$	$5.0.10^5$
Total Picophytoplankton (/ml)	$5.6.10^3$	$8.6.10^3$	$13.0.10^3$
Chlorophyll >0.7 µm (µg/l)	0.9	1.1	1.3
SDI_{3min}	9.3	19.8	31.5

flows to a circular neck and, thanks to hydrodynamic convergence, cells are separated in a sharpened capillary tube and cross the beam of light of a laser. Optical and physical signals are then collected by four photomultipliers. Two tubes detect the light diffused under two different angles: "Forward Angle Light Scatter (FSC)" for the light diffused under the axis of the incident ray and "Side Angle Light Scatter (SSC)" for the light diffused with a 90° angle. The two other tubes detect fluorescence emissions. Populations are hence differentiated according to their signals of diffusion and fluorescence [5].

For picophytoplancton and algae enumeration, samples are divided into two aliquots, fixed with formaldehyde and frozen in liquid nitroge n. Prior to analysis, the samples are rapidly thawed. Samples are then analysed using a Facsort flow cytometer (Becton Dickinson). The first aliquot is analysed directly and used for autotrophic population counts. The second aliquot is incubated for 15 min in the presence of SYBR Green I which is a dye that stains DNA, in order to obtain bacterial counts.

2.2. Raw seawater

Tests were performed on a site located next to the Mediterranean sea and pilot plants were fed through an open intake. Table 1 gives the raw seawater quality during the 6-month pilot operation.

During this period, the seawater was characterised by low particle and natural organic matter contents as average turbidity is around 0.3 NTU while average TOC is 1.2 mg/L. SDI_{3min} was quite high (average SDI_{3min} was 20) as tests were performed during a high temperature period (May to October 2007).

2.3. Conventional pretreatment process (CPP)

After pH correction from 8.2 to 6.8, the conventional pretreatment process was composed of a coagulant injection (ferric chloride at a dosing rate of 6 ppm), a 15 min flocculation (PolyDadmac polymer at a dosing rate of 0.15 ppm) and a granular dual-media filtration through sand and anthracite.

2.4. Membrane pretreatment process (MPP)

After pH correction to 6.8, seawater was pretreated by a MF pilot plant which consisted in an immerged dead-end membrane filtration with an out/in membrane module made up of PVDF hollow-fibres with a 0.1 µm nominal pore size. The active membrane area was 27.9 m^2 and the permeate flux was set up at 50 L/h/m^2. Every 30 min, backwashes were operated with air at 3.5 m^3/h and water at 2 m^3/h. Chemical enhanced backwashes were also performed once a day at 100 ppm chlorine. Over the period of testing, the specific flux of the MF unit ranged between 80 L/h/m^2/bar and 50 L/h/m^2/bar.

2.5. Reverse osmosis pilot plants

Each pretreatment process fed a RO pilot plant. Each RO pilot plant consisted in a 5 µm cartridge filter followed by a pressure vessel with a single 4 inch Dow Filmtec SW30HR LE-4040 RO membrane module. The two RO pilot plants were strictly operated under the same conditions: the feed flowrate was 750 L/h and the conversion rate was fixed at 20%, which gave a permeate flux of 19.6 L/h/m^2.

3. Main results and comments

3.1. Seawater quality at the outlet of each pretreatment

3.1.1. Conventional analytical parameters

The following table (Table 2) shows the average seawater quality at the outlet of CPP and MPP in terms of SDI, turbidity and particle counts.

This table shows even if the turbidity at the outlet of CPP and MPP permeate is the same (0.03 NTU), MPP provided a much better SDI decrease of the raw seawater as average SDI_{15} was 2.5 (3.5 at CPP outlet) with 94% of SDI_{15} below 3 (only 25% at CPP outlet). This observation is consistent with the previous studies on seawater membrane pretreatment reporting low SDI at the outlet of MF or UF membranes. MPP permeate also presented a lower particle count than the water at the outlet of CPP which is consistent with the previous results on SDI.

3.1.2. Advanced analytical parameters

As previously said, even if widely used, SDI parameter may not be accurate regarding the foulants likely to create organic and biological fouling. This is

Table 2
Average seawater quality at the outlet of CPP and MPP.

	SDI_{15}<3	SDU_{15}<3.5	Average SDI_{15}	Turbidity (NTU)	Particle > 1µm count (/ml)
CPP	25	55	3.5	0.03	160
MPP	94	99	2.5	0.03	70

why the seawater samples at the outlet of CPP and MPP were analyzed with advanced analytical tools in order to better characterize their NOM and microorganism contents. The following table (Table 3) shows the average seawater quality at the outlet of both pretreatments in terms of DOC, polysaccharide, total bacteria, total picophytoplankton and chlorophyll removal compared to raw seawater.

This table shows that the membrane pretreatment provided a better microorganism removal than CPP in terms of bacteria and picophytoplankton content (1.8 log bacteria removal for MPP vs. 0.6 log for CPP and more than 4 log plankton removal for MPP vs. 0.8 log for CPP).

Table 3 also shows that bacteria and picophytoplankton removal were more relevant for selection and optimization of pretreatment process as compared to chlorophyll removal which was somewhat similar for the two pretreatments (chlorophyll content at the outlet of both pretreatment units was either very close or below limit detection - 0.006 µg/L).

Lastly, the dissolved organic matter removal was significantly lower at the MPP outlet compared to CPP outlet: 13% decrease in DOC with CPP as compared to less than 5% with MPP. This explains the low corresponding polysaccharide removal which was only 12% for MPP permeate as compared to 38% for CPP. Consequently, MPP permeate presented a higher organic load.

3.1.3. Impact of conventional and membrane pretreatments on the RO process

After each pretreatment, seawater was pumped to an RO pilot unit. For both RO units, pretreated seawater is first filtered through a 5 µm cartridge filter before being pressurised though a high pressure pump upstream of the RO module. Fig. 1 presents the evolution of the pressure drop across the cartridge filters fed by CPP pretreated seawater and MPP permeate.

Fig. 1 shows that pressure drop remained quite stable around 0.2–0.3 bar during the first 2 months for both cartridge filters. After 2 months of operation, the pressure drop across the cartridge filter fed by CPP dramatically increased to 1.5 bars in 1 month which led to a replacement of the cartridge filter to continue the operation of the RO pilot plant. On the contrary, pressure drop across the cartridge filter fed by MPP permeate presented a slow and continuous increase to 0.6 bar during the following 4 months, which did not imply a replacement. This shows that the cartridge filter fed by CPP fouled more rapidly than the cartridge filter fed by MPP permeate.

On the contrary, the evolution of the longitudinal pressure drop along the two RO membranes fed CPP and MPP permeate did not show any difference during the 6-month operation of the RO pilot plants: pressure drop was initially at 0.09 bar and slowly increased to 0.1 bar for both RO membranes after 6 months. This shows that no fouling leading to a dramatic increase of longitudinal

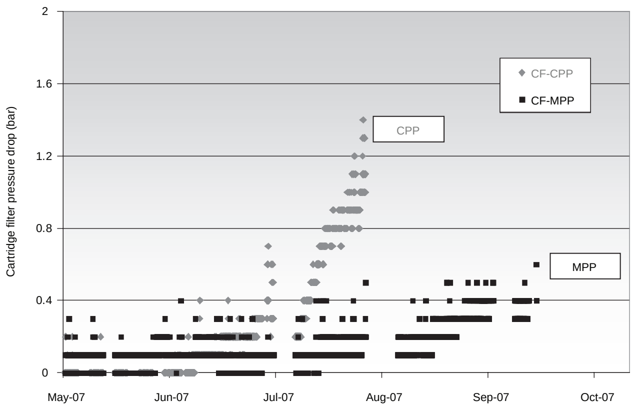

Fig. 1. Evolution of the cartridge filter pressure drop for CPP (in grey) and MPP (in black) pretreated seawater.

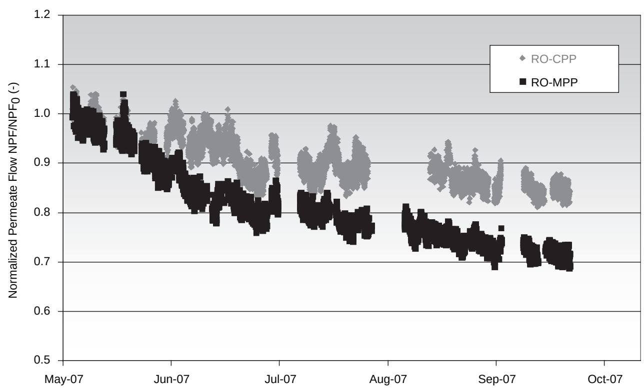

Fig. 2. Evolution of NPF/NPF_0 for the RO membranes fed by CPP (in grey) and MPP (in black).

Table 3
Average seawater quality at the outlet of CPP and MPP.

	DOC (%)	Polysac. (%)	Bacteria (Log)	Plankton (Log)	Chlorophyll %
CPP	13	38	0.6	0.8	93
MPP	< 5	12	1.8	> 4	> 95

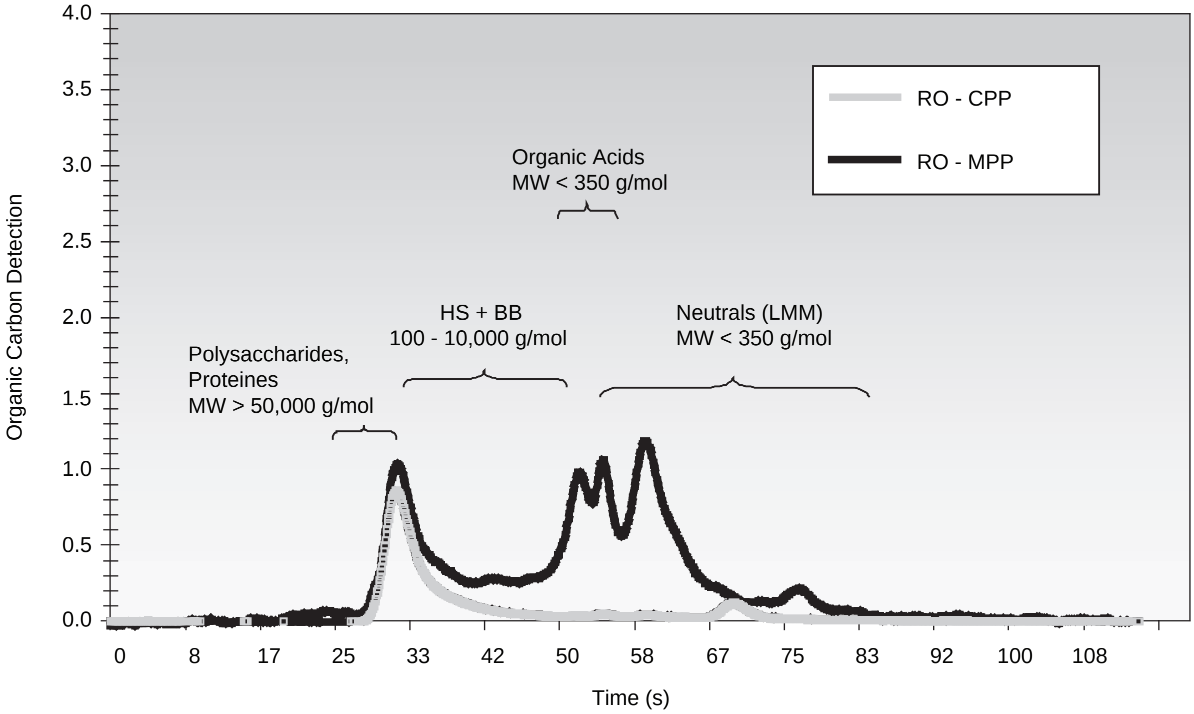

Fig. 3. LC-OCD analysis of the deposit at the surface of the RO membranes fed by CPP (in grey) and by MPP (in black).

pressure drop occurred for both RO membranes during the testing period.

Fig. 2 presents the profile of the normalized permeate flow (NPF)/(NPF_0) for each RO membrane during the 6-month study. NPF is the RO permeate flow normalized in terms of temperature correction factor (TCF) and net driving pressure (NDP).

Fig. 2 shows that the NPF of the RO membrane fed by MPP permeate decreased by 30% during the 6-month test while it only decreased by 15% for the RO membrane fed by CPP. Therefore, despite a better seawater quality at the outlet of MPP as quantified with SDI and microorganism removal, the RO unit fed by MPP showed a more pronounced decline in performance as compared to the RO unit fed by MPP.

To better understand why the RO membrane fed by MPP fouled more rapidly than the RO membrane fed by CPP, the two membranes were autopsied at the end of the 6-month study. Fig. 3 presents the LC-OCD analysis performed on the deposit which has been extracted at the surface of each RO membrane.

The analysis of the deposit on each RO membrane surface by Liquid Chromatography revealed that the concentration of Dissolved Organic Carbon was five times higher on the deposit on the MPP fed membrane (1.0 μg/cm^2) than on the CPP fed membrane (0.2 μg/ cm^2). The deposit on the CPP fed membrane was mainly made of organic molecules of high molecular weight (>50,000 Da) like polysaccharides. The deposit on the MPP fed membrane was constituted by these high molecular weight organics but also by organics with a smaller molecular weight (<350 Da) which were not found on the CPP fed membrane.

These results show that, despite a better seawater quality in terms of SDI and microorganism content, the membrane pretreatment did not retain NOM as well as the conventional pretreatment. This resulted in a more pronounced organic fouling on the RO unit fed by MPP.

4. Conclusion

MF/UF membranes have been successfully applied in pretreatment of surface water or wastewater for many years. The development of desalination activities and the evolution of membrane technologies to cost-competitive processes have led to an increased interest of membrane pretreatment for SWRO desalination. According to the results presented in this paper, whereas membrane pretreatment provided a better SDI abatement than conventional pretreatment, the comparatively lower removal for organic matter appears to have induced a higher extent of organic fouling on the RO membrane. This study also demonstrates the advantages and interest for the use advanced seawater characterization (i.e. NOM characterization in pretreated water) as well as for the use of membrane autopsies during pilot-scale studies aiming at comparing the performance of pretreatment processes.

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