Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1173382

57 (2016) 22902–22908
October

Taylor & Francis
Taylor & Francis Group

Use of innovative inge® Multibore® ultrafiltration membranes for the treatment of challenging seawater

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Received 20 April 2015; Accepted 17 March 2016

ABSTRACT

Ultrafiltration (UF) has established itself as one of the key technologies in the water treatment industry over the last decade, providing superior filtrate water quality regardless of fluctuations in the feedwater quality and protecting downstream treatment steps. UF has demonstrated its advantages as seawater reverse osmosis pre-treatment for desalination application improving reverse osmosis membranes performances while extending their service life. In-depth knowledge of polymeric chemistry is mandatory for developing, manufacturing and operating new membranes. On-site evaluation of membrane performance on real water is also essential. Seawater properties can vary significantly depending on location and region. This makes it very important to pilot in order to understand the challenges and how to address them. This paper presents results obtained at different sites operating on seawater under particularly difficult conditions using inge® Multibore® membranes. The study describes membrane behavior when operated during algae blooms, during a monsoon period and during extreme low water temperatures (0°C). It presents process adjustments realized to optimize the overall performance. The study shows that system optimization yields stable and long-term operation on challenging seawater without pre-treatment upstream of the UF membranes.

Keywords: Algae bloom; Membrane; Ultrafiltration; Seawater; System optimization

1. Introduction

For more than 30 years, microfiltration and ultrafiltration (UF) membranes have been considered as an alternate solution to conventional water treatment technologies for municipal drinking water production. Drinking water is also produced from seawater using reverse osmosis (RO) membranes. Typically, seawater was pre-treated using conventional technology consisting of clarification, sand filtration, and cartridge filters prior to RO membranes. Fifteen years ago, Furukawa [1] estimated the global total installed capacity of desalination plants at the end of 2003 to be in the range of 10 million m^3/d. According to Bennet [2], the worldwide installed capacity of desalination plants reached 80 million m^3/d by the end of 2012, bringing the worldwide number of desalination plants to more

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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.

1944-3994/1944-3986

than 16,000. For many years, UF is considered as an alternate solution to conventional treatments for seawater reverse osmosis pre-treatment.

Compared to conventional pre-treatments (clarification, dissolved air flotation, and multimedia filtration), UF membranes have demonstrated an incomparable long-term and stable operation treating all types of water, from underground water, surface water, secondary effluent wastewater to seawater.

This paper compares the performance of inge®'s membranes filtering seawater with or without the addition of the coagulant ferric chloride.

2. Plants description

This paper compares operational results of four plants. All plants operated on seawater but from different locations in the world: Bohai Bay nearby Taiwan, Gulf of Oman, Gulf of Guinea close to Accra in Ghana, and Gulf of Kutch close to Jamnagar. All plants are equipped with inge®'s low-footprint T-Rack® (Fig. 1) containing inge®'s dizzer® modules.

The membranes enclosed in the modules are hollow fibers with a nominal pore size of approximately 20 nm, made of modified polyethersulfone and spun by means of a non-solvent induced phase separation technique under inge®'s unique patented Multibore® fiber configuration combining seven individual capillaries in a highly robust fiber (Fig. 2). Such arrangement significantly increases the membrane's mechanical stability and eliminates the risk of fiber breakage. The capillaries have an internal diameter of 0.9 mm or 1.5 mm. The results presented in this article were obtained with modules containing 0.9 mm internal diameter Multibore® membranes.

The water to be treated is filtered in pressure-driven inside-out mode through the capillaries and disperses laterally through the pores of the membrane. The foam-like support material (Fig. 3) is porous enough to ensure a slight loss of transmembrane pressure (TMP), which makes this material unique on the market.

In three out of four plants seawater was taken directly from an open intake without any further pre-treatment steps upstream of the membrane filtration units except a typical 150–250 μm pre-filtration step with automatic backwash disk filters to protect the fibers. Coagulant ($FeCl_3$) is added upstream the membranes at Site 1 depending on the water quality and on the flux (J) applied. Site 2 and Site 3 have the opportunity to optionally add ferric chloride as coagulant. This inline coagulation process directly followed

Fig. 1. Typical T-Rack®.

Fig. 2. Multibore® fibers.

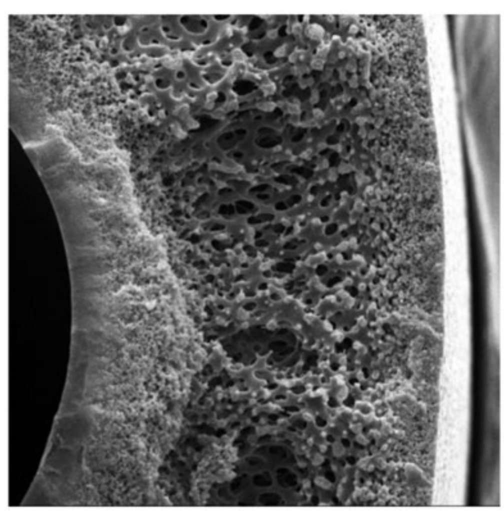

Fig. 3. Scanning Electron Microscopy (SEM) cross-section.

Table 1
Seawater quality at four different pilot sites

	Site 1 Bohai Bay	Site 2 Gulf of Oman	Site 3 Gulf of Guinea	Site 4 Gulf of Kutch
pH	8.0	8.2	8.1	7.8–8.2
Temperature (°C)	0–25	22–35	20–29	18–33
Turbidity, NTU	Avg. ~18.3 (max. 380)	1–3	Avg. <20 (max. 50)	<5
Conductivity (mS/cm)		52–60	56	58
TSS (mg/L)	12–92	~6	<25	<5
TOC (mg/L)	1–3		<15	
DOC (mg/L)		1–3		
COD (mg/L)	1–4	<30	50–100	<30

Table 2
Operating parameters

	Site 1	Site 2	Site 3	Site 4
Prefiltration (μm)	200	250	150	200
Flux (L/m^2 h)	80	80	74–80	72
Backwash frequency (min)	60	35–60	45–90	65
Coagulation w/ $FeCl_3$ (mg Fe(III)/L)	0.5–2	No (optional)	No (optional)	No
Recovery (%)	>94	>95	>93	>96
CEB frequency (d)	1	1–2	1	1

by UF is known in the market as hybrid process. The usage of ferric chloride is highly dependent on the raw water condition in regard of the organic content and inge® recommends in most cases the optional provision of coagulant dosage equipment. At Site 4, the treatment chain consists of lamella clarification with coagulant addition followed by a combined dissolved air flotation—gravity multi-media filter (GMF) then membrane filtration.

Seawater quality entering the membrane filtration units at different sites is summarized in Table 1. As anticipated, one can note that seawater quality strongly varies from location to location mainly regarding turbidity, total suspended solids (TSS) and organic content measured as total organic carbon (TOC), dissolved organic carbon, and chemical oxygen demand (COD). Site 1 and Site 2 experienced intermittent algae bloom.

Plant operating parameters are presented in Table 2. Flux and backwash frequency were defined during previous piloting phases (Site 1, 2, and 4) or based on inge® system design (ISD) criteria so as to maintain a stable permeability over time while avoiding frequent clean-in-place (CIP). Depending of the seawater quality, flux ranges from 70 to 80 L/m^2 h as a function of raw water temperature and backwash frequency from 35 to 90 min. Typically, chemical enhanced backwash (CEB) was performed once a day or once every other day. A CEB is a two-sequence protocol. A caustic chlorinated backwash is first performed (NaOCl: 20-50 mg/L at pH 9.5–10) followed by an acid backwash (H_2SO_4 at pH 2–2.3).

3. Plant operation

3.1. Site 1

The plant is operated on seawater where temperature varies from 0°C up to 25°C depending on the season. The seawater turbidity ranges from few NTU up to hundreds. Typically, turbidity is between 50 and 200 NTU from mid-November to mid-March. From mid-March until end of June, turbidity stays below 30 NTU. From July to mid-November, the turbidity starts to increase ranging from 5 to 75 NTU.

By plotting seawater turbidity against seawater temperature (Fig. 4), one can see that the higher turbidity is concurrent with the lowest water temperature resulting in drastically more difficult operating conditions for the UF units.

Under these raw water conditions during the winter time (very high turbidities at very low temperatures), the process could be operated at stable conditions with a TMP value between 400 and 600 mbar (resulting in a permeability between 200 and 300 L/h m bar) at a constant flux rate of 66 L/m^2 h

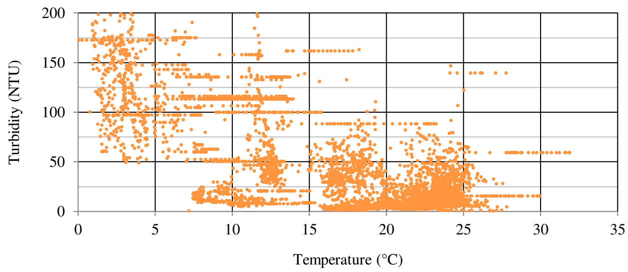

Fig. 4. Site 1—Seawater turbidity vs. seawater temperature.

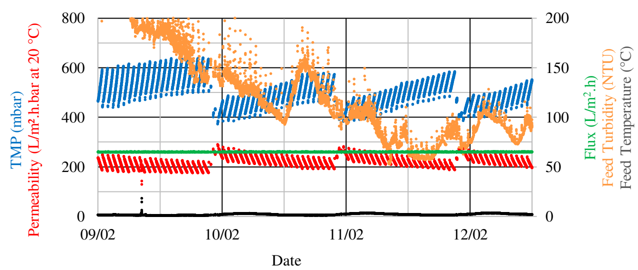

Fig. 5. Site 1—Operation at high turbidity and low temperature.

with in-line addition of 2 mg Fe(III)/L and 30 s contact time in the pipe (Fig. 5).

Different operating conditions have been tested during the one-year piloting period. During the first weeks, the plant was operated at a flux rate of 60 L/m^2 h without any coagulant addition upstream the membranes (Fig. 6).

Then the flux was increased to 70 L/m^2 h starting without any coagulant addition upstream the membranes then with 1 mg Fe(III)/L ferric chloride addition (May, 28th, 2014). On Fig. 7 one can see the beneficial effect of 1 mg/L ferric chloride addition associated with a quick decrease in the TMP and increase in the permeability. This confirms what has been observed at various other locations. Knowing that operation without coagulant addition will result is a fast clogging of the surface of the membranes, it was decided not to compare the membrane behavior with or without coagulant addition.

The flux was further increased to 80 L/m^2 h (Fig. 8) associated with an increased ferric chloride addition at 2 mg Fe(III)/L. Permeability remained in the range of 200–300 L/h m^2 bar at 20°C (250–350 mbar TMP).

In addition it should be mentioned that an online algae analyzer (Type "bbe Moldaenke," based on photometric fluorescence measurement) was installed and operated during the entire piloting. During an algae bloom period in autumn 2014, an average dissolved total chlorophyll concentration of 2–3 µg/l, with peak concentrations of 9 µg/l could be measured. Based on manufacturer's experiences and calibration tests, this corresponds to an algae cell concentration of 2×10^6–3×10^6 algae cells/l (peak value: 9×10^6 algae cells/l). Under these feedwater conditions (increased organic content and algae presence), the UF showed stable performance with the above-mentioned settings at 80 L/h m^2.

A last trial was performed at 95 L/m^2 h with the addition of 2 mg Fe(III)/L. One can note an increase in the TMP to around 500 mbar still showing stable

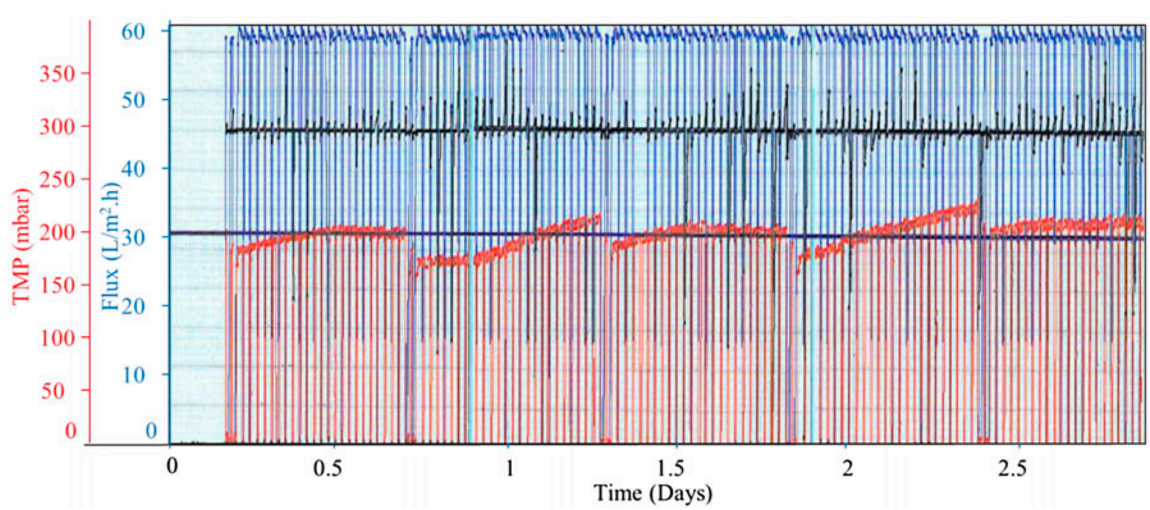

Fig. 6. Site 1—Operating parameters at a flux rate of 60 L/m^2 h (no coagulant).

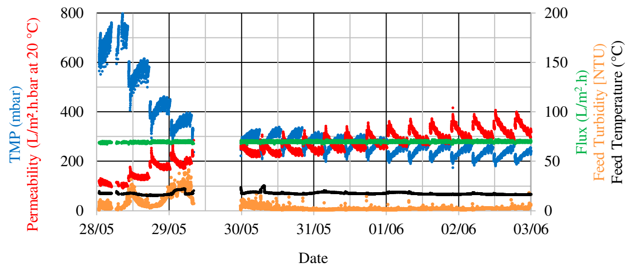

Fig. 7. Site 1—Operating parameters at a flux rate of 70 L/m^2 h and 1 mg Fe(III)/L.

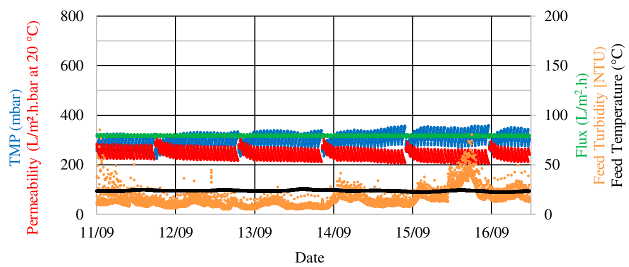

Fig. 8. Site 1—Operating parameters at a flux rate of 80 L/m^2 h and 2 mg Fe(III)/L.

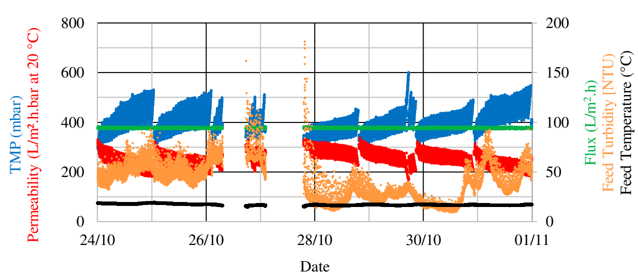

Fig. 9. Site 1—Operating parameters at a flux rate of 95 L/m^2 h and 2 mg Fe(III)/L.

system operation (Fig. 9) even during frequent turbidity spikes.

As mentioned in Table 2, the recovery was above 94% in all operating modes. No clean-in-place cleaning (CIP) was necessary during the entire piloting period of almost one year. The membrane permeability could be maintained continuously by just operating at the normal settings (CEB sequence, CEB chemical concentration and soaking durations).

3.2. Site 2

Site 2 plant was designed to operate at an average feed flux of 80-85 L/m^2 h. Over the two-month period

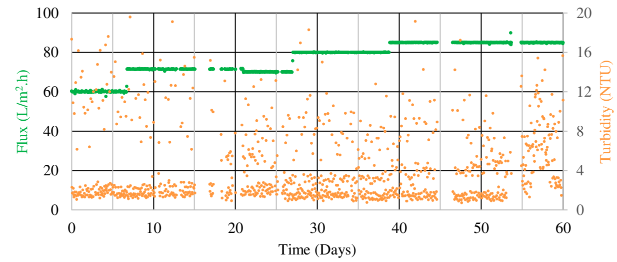

Fig. 10. Site 2—Seawater turbidity and flux.

during which the plant was studied, the feedwater turbidity (Fig. 10) remained rather low and stable around 2 NTU, while experiencing regular short duration turbidity spikes up to and above 20 NTU.

The feed flux (Fig. 10) was progressively adjusted from 60 to 85 L/h m^2. During the first 30 d of operation, the permeability (Fig. 11) remained stable in the range 300-500 L/m^2 h bar at 20°C corresponding to a TMP ranging from 100 to 200 mbar.

After that period, due to more frequent and higher turbidity spikes, at a flux of 85 L/h m^2, the permeability slightly dropped in the range 200–400 L/h m^2 bar at 20°C and the TMP varied from 150 to 300 mbar.

During the 60 d period, the recovery was always above 95% (Table 2), showing the efficiency and advantages of the overall process and associated parameters in minimizing water losses.

3.3. Site 3

Site 3 plant is equipped with 10 T-Rack® 3.0 containing each 144 dizzer® modules (Fig. 12). The plant is designed for an average flux rate of 74 L/m^2 h based on a feedwater turbidity <20 NTU (TSS < 25 mg/l) and a TOC < 15 mg/l.

Due to delays in the intake construction work, the UF system was fed from a temporary intake (Fig. 13) water basin (pond) and operated during the five-month commissioning phase with much worse feedwater qualities (turbidity 20-50 NTU, COD up to 100 mg/l) than those specified in the tender documents.

The UF membranes showed stable conditions and were continuously in operation at flux rates up to 80 L/h m^2, more frequent backwashes resulting in a recovery rate of approximately 90% to produce the necessary filtrate output for the downstream RO plant.

Fig. 14 shows, over an 11-week period, measurements of the permeability of each of the 10 lines. Depending on the raw water quality, the sequence of UF operation and exact time at which the daily CEB cleaning procedures happened, the permeability of all

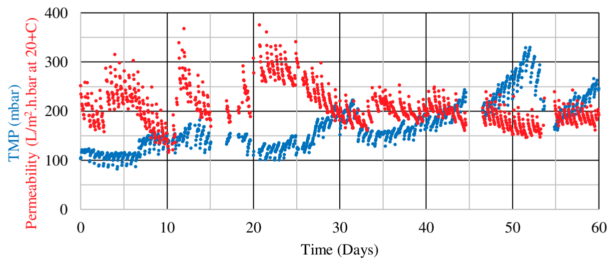

Fig. 11. Site 2—Permeability and TMP.

Fig. 12. Site 2—inge® T-Rack® 3.0.

Fig. 13. Site 2—temporary intake.

lines were between 250 and 500 L/h m^2 b at 20˚C. No CIP was performed during the whole period.

After completion of the intake system the feedwater quality improved significantly and all operational parameters were set to the original design values.

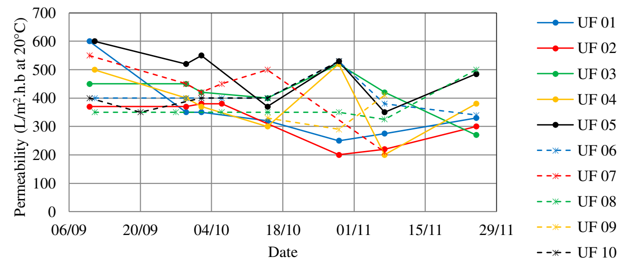

Fig. 14. Site 3—Permeability during commissioning phase.

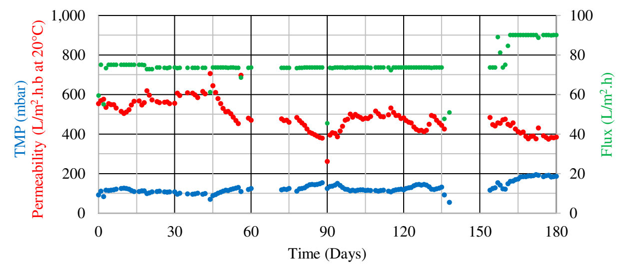

Fig. 15. Site 4—Permeability, TMP, and flux.

Since the beginning of the year 2015, the system is producing 100% UF filtrate capacity (135,000 m^3/d).

3.4. Site 4

Site 4 is equipped with 33 T-Rack® of 124 dizzer® modules producing 18,750 m/h (120 MGD) UF filtrate in total.

As previously mentioned, compared to the other three sites which have no pretreatment upstream the UF system, the membranes at Site 4 treat water pretreated by lamella clarification with coagulant addition followed by a combined dissolved air flotation—GMF. This was decided due to a very fluctuating and difficult raw seawater quality (COD up to 250 mg/l, turbidity from 30 to 400 NTU and more, TSS up to 100 mg/l, oil, and grease up to 3 mg/l) and a naturally given monsoon period which can imply an even worse raw water situation. The UF feedwater quality showed a turbidity <5 NTU and COD values <30 mg/l.

The UF pilot unit operation was studied over a six-month period during which the flux (Fig. 15) was set at 75 L/m^2 h during almost 160 d, then increased to 90 L/h m^2. One can see that the TMP remained stable in the range of 100-150 mbar at 75 L/m^2 h and slightly higher up to 200 mbar at 90 L/m^2 h. Over the full period, the recovery rate was always >96% and the permeability varied from 600 to 400 L/h m^2 b at

Table 3
Site 4—COD (mg/L) Measurements

	10 July 2014	11 July 2014	12 July 2014	14 July 2014
Seawater	36.65	32.61	37.51	36.60
Clarifier outlet		30.12	34.18	32.91
GMF outlet		26.29	27.51	26.70
UF outlet		5.25	6.69	5.93

20˚C. The permeability slightly dropped by less than 10% when increasing the flux just below 80 L/m^2 h.

The UF filtrate water quality showed excellent results. SDI measurements showed SDI < 2 most of the time, the requirement of SDI < 3 was met all the time. In addition, the reduction in the organic content was confirmed [3] by measuring the COD, the only technique available at the laboratory on site.

As shown in Table 3, the COD from the effluent of the multi-media filter (avg. 27 mg/l) has been further reduced by UF by almost 80% (avg. 6 mg/l in the UF filtrate). The corresponding SDI_{15} values are 3–5 after GMF and 2–3 after UF. The UF membrane acts as a COD polisher which will protect the downstream RO resulting in a better performance, less CIP cleanings, and an increased membrane service life time.

4. Conclusion

This paper demonstrates the capabilities of inge®'s dizzer® modules filtering seawater experiencing turbidity spikes and algae blooms. Depending on the seawater quality, mainly related to turbidity and the organic content, inge®'s Multibore® membranes are able to operate at an flux ranging from 70 to 90 L/m^2 h with a backwash frequency from 60 to 90 min while performing a daily chemical enhanced backwash.

Regardless of seawater origin and quality composition, permeability typically remained around 200–400 L/m^2 h bar at 20˚C and the TMP varied from 100 to 400 mbar while the recovery can be considered above 95%. Ferric chloride addition upstream the membranes might be needed on very difficult waters with high organic content to prevent from fouling and to maintain the permeability at an acceptable level. With optimized operating parameters a stable performance can be reached even with the presence of algae to a concentration of up to 9×10^6 algae cells/l.

It has been also demonstrated that under such operating parameters, only a yearly preventive CIP is necessary.

Low operating TMP and low CIP frequency result in very low running costs.

In addition, due to a better and constant UF filtrate water quality, one can assume that the RO performance could be improved, the necessary delta p reduced, and the RO service life extended.

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