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Performance of outside-in pressurized ultrafiltration in the Qingdao Pilot tests

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ABSTRACT

A new seawater desalination plant (SWDP) is to be built in Qingdao, China by Befesa Agua, S.A.U. The application of SWDP is to produce drinking water for local residents due to lack of brackish water in north China. Seawater will be treated with membrane technologies to achieve the required water quality. The key process unit operations are ultrafiltration and seawater reverse osmosis.

In order to prepare for the detailed design phase and membrane selection, a pilot study was carried out, in which various ultrafiltration product and process concepts were investigated. Among other, submerged and pressurized processes were tested, using inside-out and outside in module configurations, polyethersulfone (PES) and polyvinylidene fluoride (PVDF) fibers. Comparative results with these different technologies had been published previously.

This publication provides detailed results on the first phase of testing of one of the technologies investigated: pressurized, outside-in, PVDF-based ultrafiltration product and process. It shows performance both from a hydraulic point of view as well as the water quality characterization.

Keywords: Seawater; Desalination; Ultrafiltration; Pressurized; Cleaning; Air; Chemicals; Silt Denisty Index (SDI); Modified Fouling Index (MFI); RO - Reverse Osmosis; CIP - Clean In Place; BOD - Biological Oxygen Demand; CEB - Chemical Enhanced Backwash

1. Introduction

A new seawater desalination plant (SWDP) is to be built in Qingdao, China by Befesa Agua. It is located in the eastern part of China (Shandong Province) and it is being developed under a 25-year design build own operate (DBOO) contract between the Municipality of Qingdao and Befesa Agua in order to supply drinking water to this city with a production capacity of 100,000 m^3/d. It is situated near a seawater lagoon (Fig. 1), which is shared with another already existing factory (Soda). The lagoon that the seawater will be withdrawn from receives its inflows from the shallow waters of the bay by means of a submerged pipe, when the tide is high.

Seawater will be treated with membrane technologies to achieve the required water quality. The process chosen is seawater reverse osmosis (SWRO), combined with appropriate pre-treatment and post-treatment. The water fed to the SWRO membranes must have a minimum quality and for that reason the pre-treatment plays a crucial role in this process in order to assure the durability of the membranes and to produce the desired water. In order to optimize the pre-treatment, especially the potential ultrafiltration (UF) system, Befesa Agua has carried out a piloting program.

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Fig. 1. Qingdao location and lagoon photograph.

The main objectives of the pilot studies are validation of the performance data specified by the system suppliers and optimization of the operating parameters to achieve the most cost-effective and efficient pre-treatment for Qingdao SWDP. Partial objectives are described below:

1. Demonstrate the feasibility of UF to be used as pretreatment for the SWRO system.
2. Optimize the UF design parameters.
3. Optimize the UF flux.
4. Optimize the chemical cleaning frequency and duration.
5. Optimize cleaning protocols and hence cleaning efficiency.

The piloting program has involved various technologies, such as submerged and pressurized, inside-in and outside-in configurations from several UF technology suppliers. A summary of results of the studies carried out by BEFESA, using multiple suppliers (pressurized inside-out, pressurized outside-in, submerged) has been published elsewhere (Salas et al., 2008 and Riaza et al., 2008) and also involved a limited comparison. A performance comparison of the various different technologies is not within the scope of this publication, which focuses on a detailed review of the first phase of piloting of outside-in pressurized ultrafiltration technology. Information about comparative performance can be found from other studies (e.g. Pilutti & Nemeth 2003, Huehmer et al. 2007, Vrenkel et al. 2007, Leal et al. 2009).

The pilot study with pressurized outside-in PVDF ultrafiltration membranes focused on hydraulic aspects (mainly flux and cleaning protocols, hence above objectives 2, 3, 4, 5) and was carried out from April 2008 until September 2008 using DOW™ Ultrafiltration module SFP-2860.

Product water quality, which is relevant for the SWRO downstream design (above objective 1), is also reported: Silt Density Index (SDI) and manual product water turbidity measurements). The data of the study is complemented by additional water quality results using more advanced methods, which were obtained in a recent follow-up study (between January and April 2009) in Qingdao with the same module type DOW™ Ultrafiltration module SFP-2860.

2. Material and methods

2.1. Pilot plant

In order to optimize the UF pretreatment of Qingdao SWDP, Dow has developed a fully automatic pilot plant (allowing 24 h / 7 days uninterrupted operation) with a flow rate in the range of 3 m^3/h, using 1 module Dow™ Ultrafiltration SFP-2860. In , a flow chart of the pilot plant is shown.

The seawater is pumped from the lagoon to the raw water tank. The ferric chloride can optionally be dosed into the raw water tank. The UF feed pump provides feed water from the raw water tank into the 100 μm strainer and from there the UF membrane is supplied. The most common configuration, dead-end filtration mode had been chosen for this series of pilot tests.

Some of the UF product water is stored in a backwash tank, from which backwashes are carried out. Fig. 2 shows solid lines for pipes used in filtration mode, and dashed lines for the pipes used during the various cleaning operations. There are multiple combinations of valve positions for the various operation modes and these are not explained in more detail. The effluent from the backwashes can be collected from the top (brine) or the bottom (feed) port and is discharged. Air can, and most of the time, is used before and/or during the backwash (with top drain) in order to enhance the cleaning effect ("air scour"). Occasionally the backwash is carried out with chemicals (most typically NaOCl and acid).

All process modes except clean in place (CIP) are automated. The detailed information of the UF module type employed in this series of pilot tests is shown below in Table 1.

2.2. Analytical methodology

In order to determine the best experimental conditions, different water quality parameters have been analyzed using analytical methods recommended by APHA-AWWA-WPCF (1992) and USEPA (2007). The analyses were carried out by Befesa Agua in the laboratory located on the pilot plant site and by an external laboratory which was contracted by Befesa Agua.

The analyses mainly carried out by Dow include turbidity, silt density index (SDI) and modified fouling index (MFI). For the April 2008 to September 2008 study,

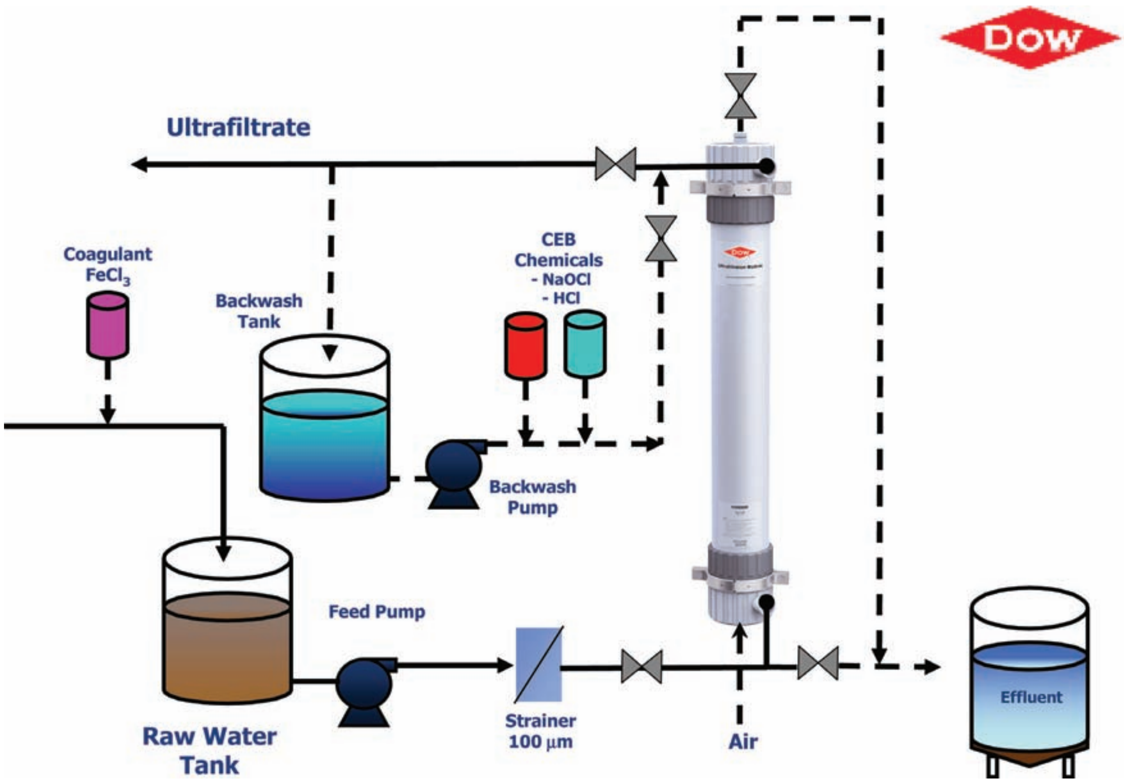

Fig. 2. Flow chart of the Dow™ Ultrafiltration pilot plant.

Table 1
UF module information.

Item	UF module
Module	SFP-2860
Fiber type	Hollow fiber
Fiber material	Hydrophilic PVDF
Pore size	0.03 µm
Active area (m^2)	51
Max. operation pressure (bar)	6.0
Product water range (m^3/h)	2.0–3.0
Max. TMP (bar)	2.1
pH range for continuous operation	2–11

which is mainly reported here, turbidity was measured using a manual turbidity test device (Hach 2100 P). Silt density index of ultrafiltration product generally followed the ASTM standard D4189 (ASTM, 2007) using the 15 min. test time.

During the later study (January 2009 to April 2009) longer test times were also recorded (up to 45 min.) for the SDI, from which also modified fouling index using microfiltration membranes (MFI-MF) was derived (Boerlage et al., 2002). For the feed water, it was not possible to characterize the SDI in the minimum time interval recommended by ASTM (2007), because the flux loss was >75% within five min. In the follow-up study, a test time of only 1.5 min. was used, which was successful. In the later study, turbidity was also measured with a high precision online instrument (HACH FILTERTRAK-660 sc).

3. Test conditions

3.1. Raw water analysis

The quality of raw water as well as the product water of the ultrafiltration (which will feed the SWRO membranes) is presented in the Table 2. The high values of both total suspended solids (TSS) and turbidity are remarkable. In addition, a very strong seasonal temperature variation between 3 and 28 ºC is displayed, which can further complicate membrane treatment because it can affect the trans-membrane pressure (TMP) in the UF system as well as the net driving force (NDF) in the RO process.

Related to the product water, the pre-treatment must decrease the values of crucial parameters such as SDI, TSS and turbidity under 3, 1 mg/L and 0.1 NTU respectively previously to reach the RO membranes. Table 2 shows a summary of crucial parameters in the

Table 2
Feed water characteristics and UF product water expectations.

Parameter	Raw water	Product water
Temperature (ºC)	3–28	-/-
SDI_{15}	-/-	< 3
TSS (mg/L)	70	< 1
Turbidity (NTU)	Maximum 25, median 5.4, standard deviation 2.1	< 0.1
TOC (mg/L)	7.5	-/-
SiO_2 soluble (mg/L)	1	-/-
Fe total (mg/L)	0.2	-/-
SiO_2 colloidal (mg/L)	1	-/-

Table 3
Sampling of UF feed during main pilot test.

Parameter	Unit	Jul	Aug	Sep
Temperature	ºC	27.1	19.8	20.5
pH	–	7.7	7.1	7.8
Turbidity	NTU	1	<1	5
Hardness (as $CaCO_3$)	mg/L	5360	5410	5010
Total dissolved solids	mg/L	33,100	39,100	31,000
BOD_5	mg/L	4	<2	<2
TOC	mg/L	<2	14	4
Oil & Grease	mg/L	<0.1	<0.1	<0.1
SiO_2 (Soluble)	mg/L	0.95	1.04	0.9

feed water (long term average), and the expectation for the product water. Table 3 shows results of samplings carried out during the main piloting (April to September 2008).

It can be seen that not for every parameter, a typical feed concentration, or product water expectation is given. E.g. SDI for feed cannot be measured according to the ASTM method, while there is no product water expectation for some of the parameters (e.g. temperature, Fe or SiO_2).

Tables 2 and 3 show substantial variation in feed water composition. Some of it is due to measurement variation; however most of it is due to the considerable changes during the day (tidal variation), due to weather (storm events) and due to seasonal factors (algae growth).

During the follow-up campaign between January and April 2009, advanced SDI and MFI-MF tests were also carried out and showed SDI values of 51 %/min (using 1.5 min test interval) and MFI values in the range of 3000 to 18,000 s/L², with an average of 7,000 s/L².

3.2. Operating flux setting over the entire test period

As an introduction, operation conditions and UF system performance over the entire test period (21 April 2008 to 24 September 2008) are shown. The testing was divided in various test periods. Operating conditions and results of each testing period will be described in detail after this introductory section.

It can be seen that the flux settings were changed in a relatively drastic manner, between a minimum of 60 and a maximum of 110 L/h/m², with middle points at 80 and 85 L/h/m². This was done in order to provide a fast and firm determination of the flux target range. During the entire five months operation, three different testing conditions were carried out:

1. Three months at 60 L/h/m², from 21 April until 16 June (test period 1 A) and from 23 August until 24 September (test period 1 B).
2. 24 days at 80 L/h/m², from 17 June until 10 July (test period 2 A) and 28 days at 85 L/h/m², from 14 July until 10 August (test period 2 B).
3. 9 days at 110 L/h/m², from 13 August until 21 August (test period 3).

3.4. Short-term flux maintenance: Backwash, air scrub, and others

The settings for the short-term flux maintenance programs over the test period are shown in Table 4.

It can be seen that backwash duration, backwash flux and forward flush flow rate were kept constant in conditions 1 (60 L/h/m²) and 2A (80 L/h/m²). Based on the learnings from phase 2 A, a high backwash duration and backwash flux were adopted for phases 2B (85 L/h/m²) and 3 (110 L/h/m²). CEB frequency was also varied, which is not shown above Table 5 but in Fig. 7.

3.5. Mid term flux maintenance: Chemical enhanced backwash (CEB)

The general sequence for chemical enhanced backwash (CEB) was a hypochlorite CEB followed by acidic CEB. The frequency adopted was 12 h except in special test intervals, when less frequent CEBs (of 24 and 120 h) were adopted. Occasionally the dosage and/or CEB flux were varied as well. The detailed conditions are shown in Table 5.

The approach described for the short-term flux maintenance was also applied for mid-term flux maintenance (chemical-enhanced backwash): higher CEB flux was used in conditions 2B and 3 ad condition 3 (110 L/h/m² also used higher chemicals concentration).

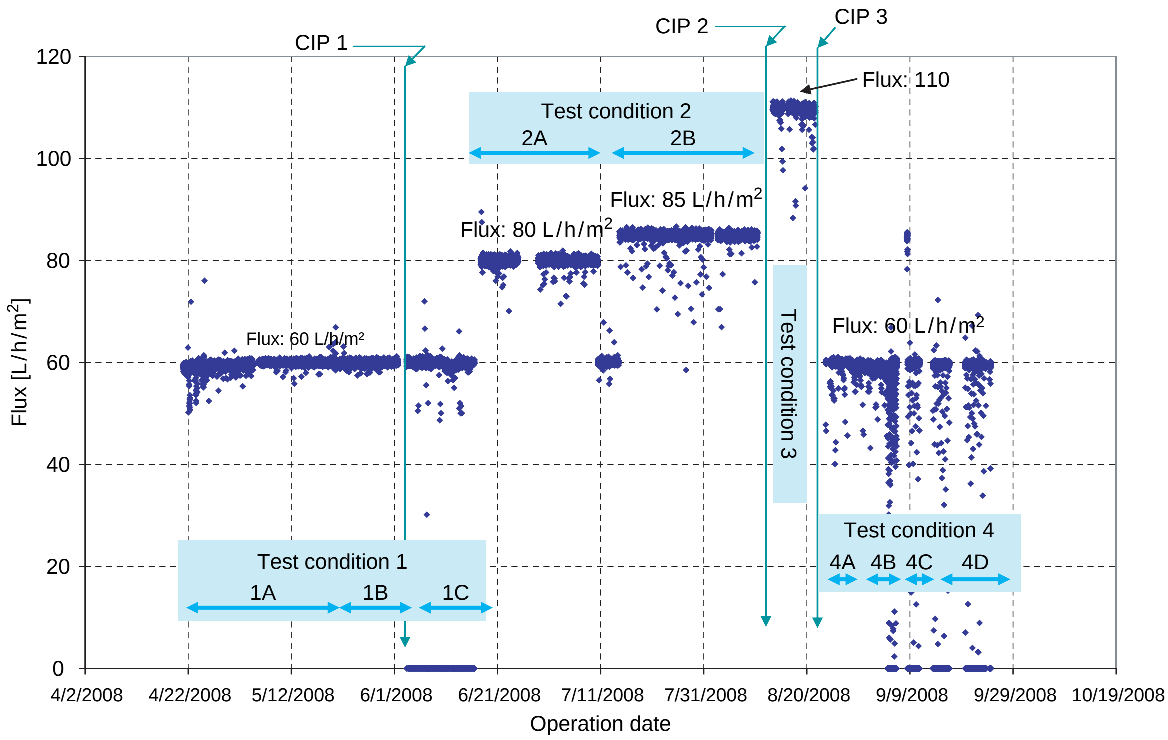

Fig. 3. Flux setting during the 4 test periods.

Table 4
Settings of short term flux maintenance programs.

Test	Testing Date		Filtration		Air scrub		Backwash		Flush		Others	
No.	Start	End	Duration, min	Flux, L/h/m²	Duration, sec	Flow rate, Nm³/h	Duration, sec	Back wash Flux, L/h/m²	Duration, sec	Forward flush Flux, L/h/m²	Fe Cl3, mg/ L	Recovery
1	21-Apr	10-May		60	30	12	45	98		60	1.5	92.9%
2	10-May	13-May		60	30	12	45	98		60	0.75	92.9%
3	13-May	16-May		60	30	12	45	98		60	0.4	92.9%
4	16-May	19-May		60	30	12	45	98		60	0	92.9%
5	19-May	1-Jun		60	30	12	45	98		60	0	93.8%
6	3-Jun	16-Jun		60	30	12	45	98		60	0	93.7%
7	17-Jun	10-Jul		80	30	12	45	98		60	1.5	94.7%
8*	10-Jul	14-Jul		60	30	12	45	98		60	1.5	92.9%
9	14-Jul	10-Aug		85	30	12	80	130		78	1.5	90.0%
10	13-Aug	21-Aug		110	30	12	80	150		98	0	90.9%
11	23-Aug	30-Aug		60	30	12	45	98		60	0	93.4%
12	30-Aug	4-Sep		60	30	12	45	98		60	0	92.9%
13	4-Sep	8-Sep		60	30	12	45	98		60	0	92.9%
14	8-Sep	12-Sep		60	(*1)		45	98		60	0	92.9%
15	13-Sep	24-Sep	30	60	30	10	45	98	40	60	0	93.4%

(*1) No air scrub performed, therefore cells left blank.

3.5. Long-term flux maintenance protocols: Clean in place (CIP) operations

During the five months testing, three clean in place (CIP) operations were carried out. These were carried out between the different testing periods in order to restore permeability back to the original value before the next test period. The three CIP operations were carried out at the following dates:

1. First CIP is performed before testing with CEB interval of 120 h at 60 L/h/m², at 2 June.
2. Second CIP is performed before testing at 110 L/h/m², at 12 August.
3. Third CIP is performed after testing at 110 L/h/m², at 22 August.

The main chemical and process characteristics of the CIP protocol are shown in Table 6.

4. Hydraulic performance of the UF system

4.1. Test condition 1 – initial two months at 60 L/h/m²

In Fig. 4, the influence of CEB frequency and coagulant dosing at 60 L/h/m² can be observed. For the influence of CEB frequency at 60 L/h/m², there are three different test phases within the test period 1:

- One month with CEB frequency of 12 h, from 21 April until 19 May (test condition 1A).
- 14 days wit only 1 CEB, from 19 May to 1 June (test condition 1B).
- 14 days with CEB every 120 h, from 3 June till 16 June (test condition 1C).

It can be seen that the test starts at a fairly low permeability of only 80 L/h/m²/bar. This is possibly due to a permeability reduction from the initial expected value of 200 L/h/m²/bar during commissioning of the system.

Despite the low starting value, membrane permeability at around the starting value of 80 L/h/m²/bar is maintained during about one month testing with the 12 h CEB interval at 60 L/h/m² (period 1 A).

From 19 May to 27 May, the CEB is stopped, but permeability is unstable and decreases to about 50 L/h/m²/bar, which corresponds to 55% of the initial permeability. The TMP increases from 0.8 bar to 1.4 bar since 19 May until 27 May. On 27 May, one CEB is performed, which restores permeability to 73% of the initial level, which indicate that the foulant is not well removed by CEB. From 27 May to 1 June, CEB is stopped again and the performance is similar to the former testing without CEB, permeability drops again. The reduction in permeability during the condition without CEB (1B) might also partly be due to the turbidity increase during that period (from 2.5 to 7 NTU).

Before the next test condition (1C), the first CIP is performed on 2 June. This restores permeability from

Table 5
Settings of chemical enhanced backwash.

Test No.	Testing Date		CEB A						CEB B					
	Start	End	Chemical	Frequency, (hour)	Duration for CEB A, (min)	Soaking time, (min)	Flux, (Lmh)	Dosage ,(mg/Ll)	Chemical	Frequency, (hour)	Duration for CEB B, (min)	Soaking time, (min)	Flux, (Lmh)	Dosage, (mg/lL)
1	21-Apr	10-May	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
2	10-May	13-May	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
3	13-May	16-May	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
4	16-May	19-May	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
5	19-May	1-Jun	(*1)						(*1)					
6	3-Jun	16-Jun	NaOCl	120	13.8	10	98	500	HCl	120	13.8	10	98	400
7	17-Jun	10-Jul	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
8	10-Jul	14-Jul	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
9	14-Jul	10-Aug	NaOCl	12	13.8	10	130	500	HCl	12	13.8	10	130	400
10	13-Aug	21-Aug	NaOCl	12	13.8	10	150	1000	HCl	12	13.8	10	150	1000
11	23-Aug	30-Aug	NaOCl	24	13.8	10	98	500	HCl	24	13.8	10	98	400
12	30-Aug	4-Sep	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
13	4-Sep	8-Sep	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
14	8-Sep	12-Sep	NaOCl	12	13.8	10	98	500	HCl	12	13.8	10	98	400
15	13-Sep	24-Sep	NaOCl	12	18	15	98	500	(*1)					

(*1) In various occasions, no CEB was carried out. These occasions are shown by blank cells in above table.

Table 6
CIP protocol.

Step	Chemicals	Concentration, (mg/L)	Flow rate, (m^3/h)	Duration
Acid	oxalic acid	20,000	1.5	(1) 60 min recirculation
	NaOH	1000		(2) 90 min soaking
Alkaline	NaOCl	2000	1.5	(3) 20 min recirculation

55 L/h/m²/bar to 205 L/h/m²/bar and TMP returns to 0.32 bar. It can be seen that the permeability reached after the CIP operation for condition 1C is higher than during the initial test condition (1A). This indicates that the modules started the test in fact with a reduced permeability, due to a potential loss of permeability during the commissioning period. This suggests that it would have been good to perform a CIP before the start of the first test period.

From 3-June to 16-June, the testing with the 120 h CEB interval is performed (test condition 1C). The performance is shown as follow:

- The permeability drops from 204 L/h/m²/bar to 112 L/h/m²/bar (45%) and TMP increases from 0.32 bar to 0.6 bar during first CEB cycle, from 3 June until 7 June.
- The permeability drops from 163 L/h/m²/bar to 102 L/h/m²/bar (37%) and TMP increases from 0.4 bar to 0.65 bar during second CEB cycle, from 7 June till 12 June.
- The permeability drops from 129 L/h/m²/bar to 98 L/h/m²/bar (24%) and TMP increases from 0.48 bar to 0.69 bar during third CEB cycle, from 12 June till 16 June.

The permeability restoration after each CEB is listed in Table 7.

The above results show that the recovery of permeability decreases with each CEB during this test condition (1C). It is expected that this decrease would continue until reaching to a stable value of permeability, if the CEB frequency of 120 h was maintained. Comparing the permeability value of the period with 120 h CEB frequency (1C) with the 12 h frequency period (1A) indicates that the general permeability level is higher during the less frequent CEB operations – but this is an unstable permeability level

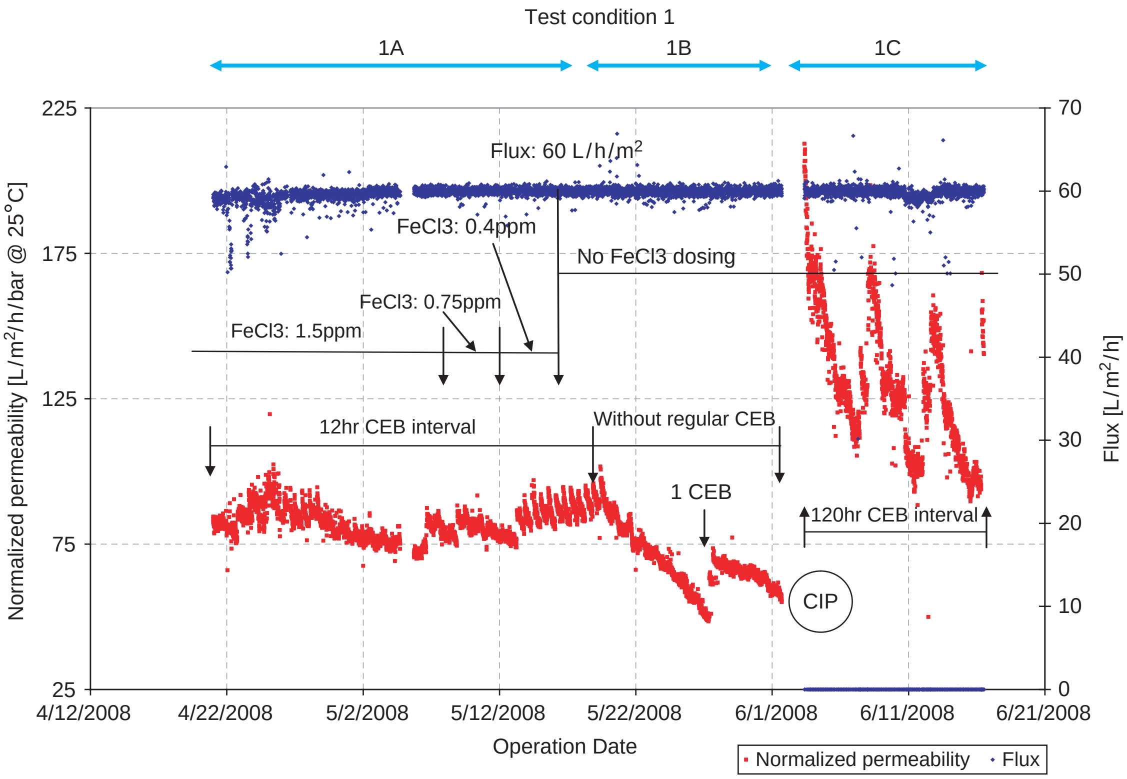

Fig. 4. Performance during test condition 1 at 60 L/h/m².

and can be explained by the CIP operation before test condition 1C.

4.2. Test condition 2 – flux of 80–85 L/h/m²

During test period 2, the flux was adjusted as follows:

- 80 L/h/m² with 12 h CEB interval, from 17-June until 10-July (test condition 2A).
- 85 L/h/m² with 12 h CEB interval, from 14-July until 10-August (test condition 2B).
- From 10-July to 14-July, a short intermediate test period with 60 L/h/m² with 12 h CEB interval was added between test periods 2A and 2B at 80 and 85 L/h/m².

Table 7
CEB cleaning efficiency in test condition 1 C.

Item	Origin	First CEB	Second CEB
Permeability after cleaning (L/h/m²/bar)	204	163	129
Recovery of permeability (based on origin)	/	80%	63%

Figure 5 presents the flux settings and the permeability over the entire test period 2.

At the beginning of the test period, permeability starts around 115 L/h/m²/bar and stabilizes at 105 L/h/m²/bar during the 24 d of testing at 80 L/h/m² in test condition 2A, the required TMP is 0.8 bar. During the short intermediate test period at 60 L/h/m², permeability is in the range of 95 L/h/m². At 85 L/h/m², the permeability starts around 90 L/h/m²/bar and apart from short fluctuation periods (18-July to 21-July and 2-August to 4-August); it decreases over the test period to about 60 L/h/m²/bar. A stable permeability is not reached at the end of this test period, and a CIP operation is required due to the high TMP of 1.5 bar, which is reached at this point. According to the above result, the UF system could operate without CIP for more than 1.5 months at the flux of 80 to 85 L/h /m² and with a CEB interval of 12 h.

4.3. Test condition 3 – 110 L/h/m²

During test condition 3, the flux was set to the maximum that was believed to be possible with seawater having the characteristics of Qingdao seawater. A CIP was done to restore the membrane permeability, from

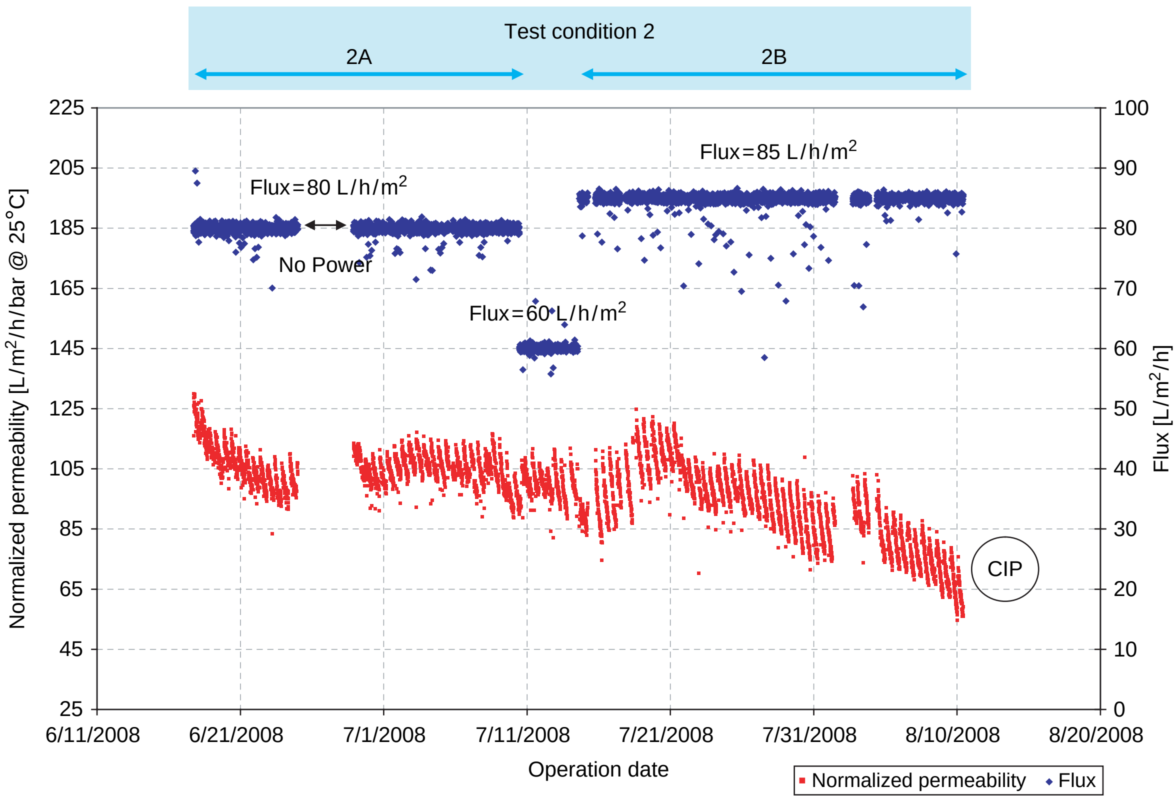

Fig. 5. Performance during test condition 2 at 80 – 85 L/h/m² flux.

the low level of about 60 L/h/m²/bar after the operation at 85 L/h/m² during test condition 2B. CIP restored a permeability of 155 L/h/m²/bar, which decreased the corresponding TMP from 1.52 bar to 0.7 bar.

Fig. 6 shows permeability over this short period of 8 d in test condition 3.

Permeability decreases from the initial 155 L/h/m²/bar to an apparently stable level of 90 L/h/m²/bar, but then a further drop to 65 L/h/m²/bar is experienced, which increases TMP to 1.65 bar and triggers a CIP operation. This result suggests that despite frequent CEB operations every 12 h, a very high CIP frequency should be expected, when designing and operating a large-scale UF plant at such a high flux of 110 L/h/m².

4.4. Test condition 4

After test conditions 2 and 3 at high fluxes in the range of 80 to 110 L/h/m², test condition 4 to the more conservative flux of 60 L/h/m², which had also been used in test condition 1. CEB frequency was maintained in the range of 12 (test condition 4B) and 24 h (test condition 4A), and at the end (test condition 4D), the acid CEB was eliminated, while a CEB frequency of 12 h was maintained. During a short interim period (test condition 4C), the air compressor failed, which allowed assessing the effect of air scrubbing. Flux settings and operational results are shown in Figure 7.

Operational results in test condition 4 are as follows:

- During the 8 d at CEB interval of 24 h (test condition 4A), permeability decreases substantially, from 140 L/h/m²/bar to around 70 L/h/m²/bar, which corresponds to a TMP increase from 0.4 to −0.85 bar.
- After the CEB frequency is increased from 24 h to 12 h (test condition 4B), permeability stabilizes at around 60 L/h/m²/bar. A double CEB was carried out instead of a CIP operation, to provide enhanced cleaning and rehabilitate permeability for the next test condition.
- Then CEB frequency was reduced again to 24 h, but the air compressor failed and air scrubbing was not carried out (test period 4 C, 8-September to 12-September). Permeability decreased extremely fast from 145 L/h/m²/bar to a very low value of

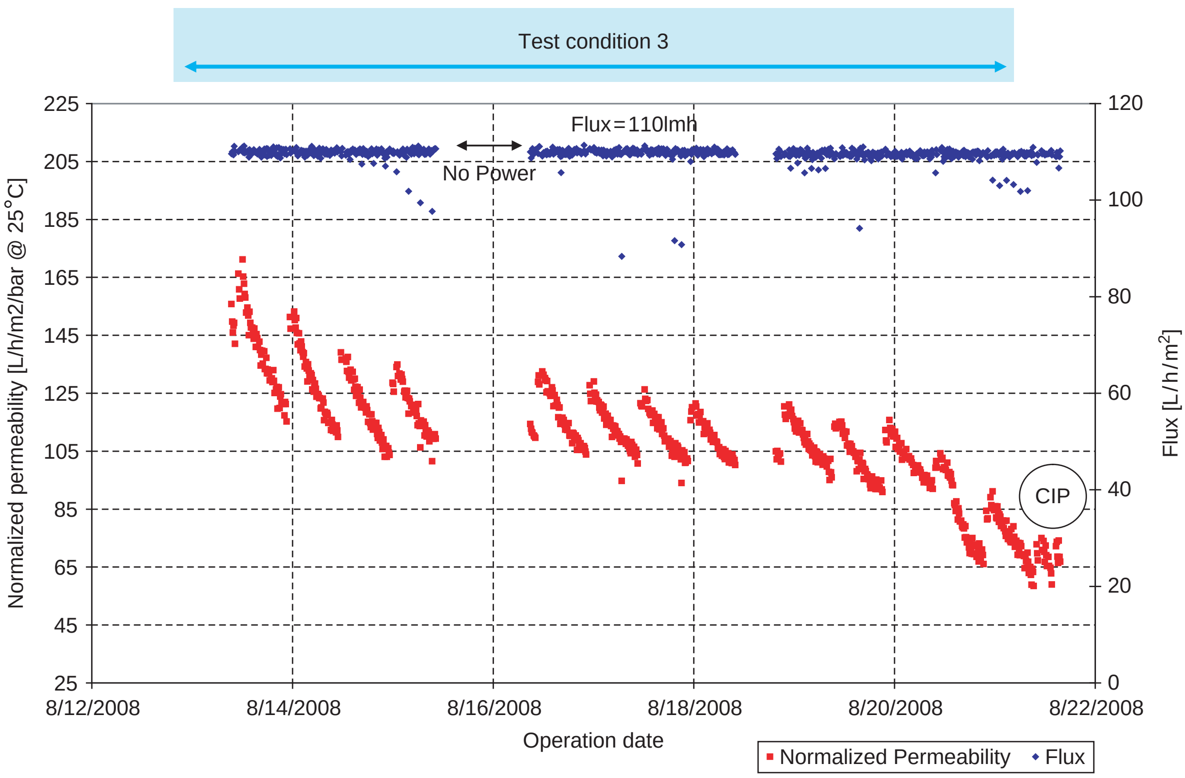

Fig. 6. Performance in test period 3 at 110 L/h/m².

only 30 L/h/m²/bar, which corresponds to a TMP increase from 0.4 bar to more than 2 bar in only 3 d operation. Comparing test results of test period 4A and 4C shows that air scrubbing plays an extremely important role in maintaining permeability of ultrafiltration modules.

- The only difference between test condition 4B and test condition 4D is that in condition 4D there is no acid CEB, and only oxidative CEB. The acceptable permeability of 80 L/h/m²/bar suggests that acid CEB might be cancelled or its frequency significantly reduced for this type of water.

4.5. Clean in place (CIP) operations

During the above described four main test conditions, three CIP cleanings are mentioned which were carried out at various stages:

- Between test conditions 1B and 1C (both 60 L/h/m²).
- Between test condition 2B (85 L/h/m²) and 3 (119 L/h/m²).
- Between test conditions 3 (110 L/h/m²) and 4 (60 L/h/m²).

The main chemical and process characteristics of the CIP protocol have already been shown in Table 6.

Permeability before and after cleaning is shown in Fig. 8.

It is observed that permeability is well restored by the CIP operations. The increase of permeability by the CIP amounts to 150% (CIP 1, 60 L/h/m²), 90% (CIP 2, 85 L/h/m²) and 48% (CIP 3, 110 L/h/m²). It can be observed that the later cleanings, which are also the ones at higher flux operation, are less effective. It is assumed that the higher flux condition might have required more stringent cleaning conditions.

In order to study the main foulant, raw water and spent UF backwash samples were tested in the Dow laboratory in Huzhou. Results are shown in Fig. 9.

Table 8 shows that COD_{Mn} and dissolved Silica increase somewhat (concentration factors of 3.3 to 4.), and Colloidal Silica and Fe increase significantly (concentration factor 13 to 28). Based on the operational and backwash flux settings, the recovery should be 96% and the theoretical concentration factor 25. In terms of mass

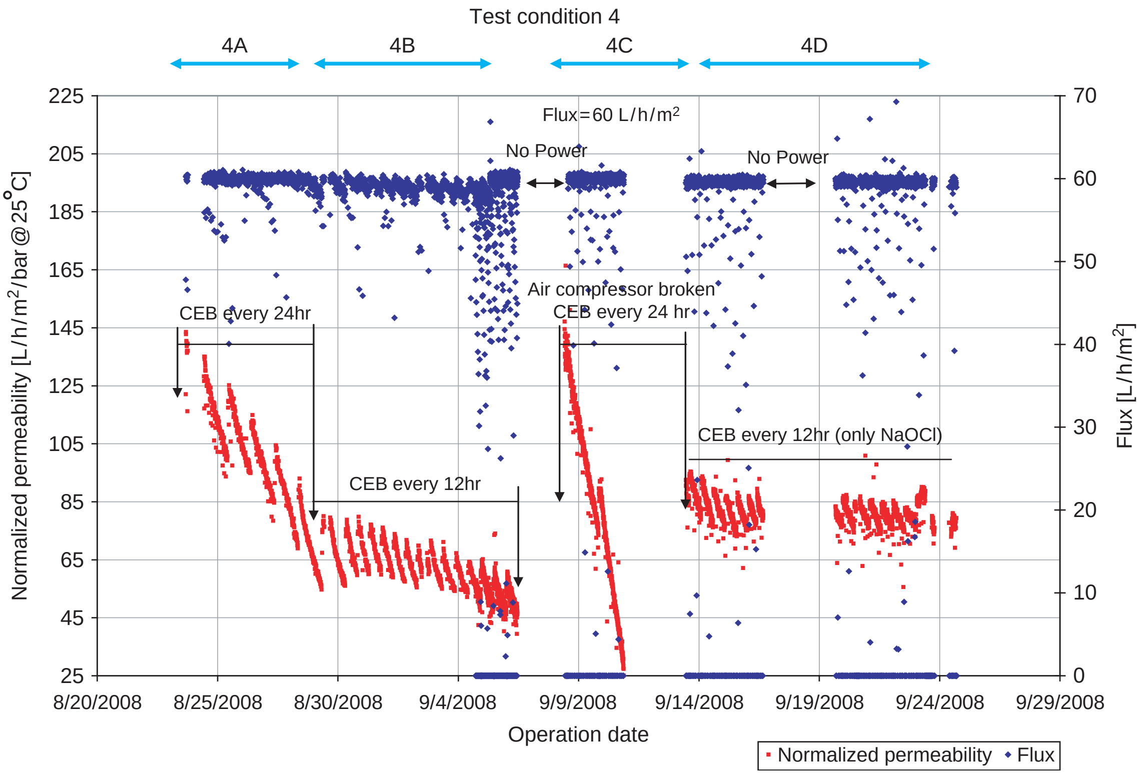

Fig. 7. Operational results in test condition 4.

loading, the main foulants accumulated on the membrane and removed by the backwash are of organic nature (based on COD) and Fe. Based on organics and Fe being the main foulants, the choice for NaOCl, NaOH and oxalic acid seem to be the appropriate CIP solution, which is also confirmed by the good recovery of permeability in the CIP operations.

5. Product water quality of the UF system

5.1. Turbidity

Turbidity of feed water and permeate water was monitored at the beginning and the end of the testing program, using a manual turbidity instrument. Results are shown in Figure 9.

Significant variation of feed turbidity in the range of 3 to 11 NTU can be seen. The average is 5.4 NTU with a standard deviation of 2.1 NTU. Despite this variation, product water quality is relatively stable, in a range of 0.1–0.2, except for a short period where levels of up to 0.3 NTU were observed (this was during the test condition with highest flux of 110 L/h/m² and it is possible that the high TMP applied in this period could have caused more passage). This stability can also mathematically be shown, by a linear correlation of product and feed water which yields a regression coefficient of only 4%. This product water stability is a well known aspect of ultrafiltration pretreatment, and presents a significant advantage over media filtration, which shows stronger dependence on the feed water, as has been widely shown in the literature (e.g. Huehmer et al. 2007, Vrenkel et al. 2007).

The lower product water quality values of 0.10–0.15 NTU are coming close to the detection limit of around 0.1 NTU of the HACH 2100 P device, which was used for the manual measurements. More recent tests at the Qingdao SWDP in a second series of experiments with a higher precision online instrument (HACH FILTERTRAK 660 sc) have shown that product water turbidity values with the more precise online instrument are significantly lower (in the range of 0.02 NTU) as opposed to the values around 0.15 which were measured with the manual hand device. This suggests that the product water quality could be significantly better than reported above. The use of manual low precision instruments should be avoided for ultrafiltration product water, and

Table 8
Analysis of raw water and UF backwash.

Item	Raw water concentration, (mg/L)	UF backwash concentration, (mg/L)	Ratio
COD_{Mn}	4.72	15.6	3.3
Dissolved Silica	0.08	0.39	4.9
Colloidal Silica	0.04	0.53	13
Fe	0.4	11.2	28
Mn	<0.02	<0.02	
Al	0.08	0.13	

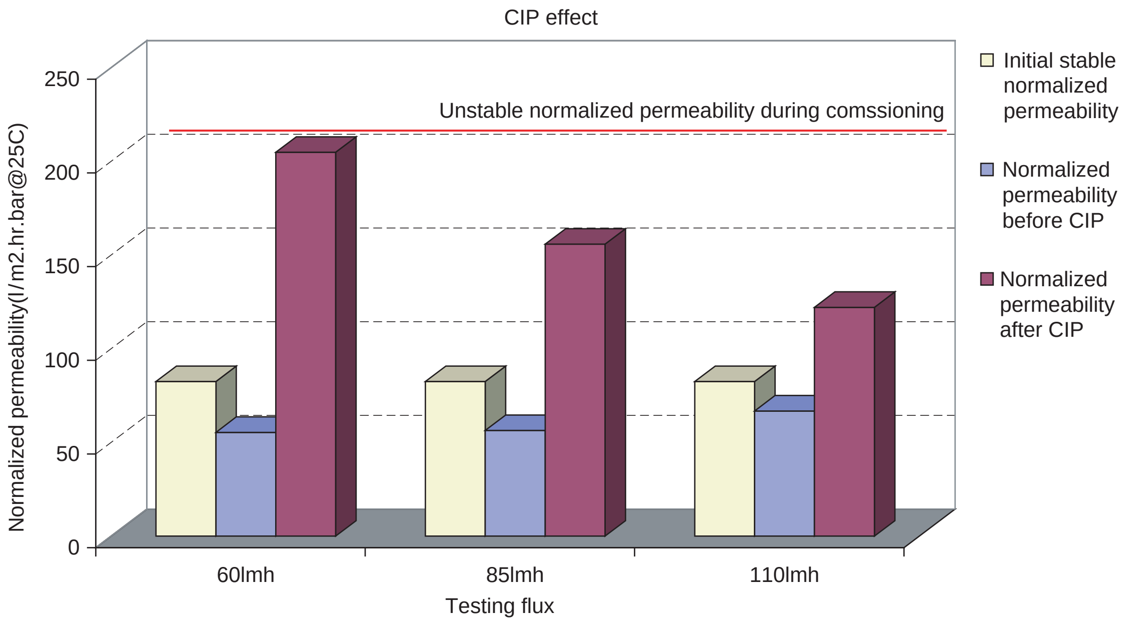

Fig. 8. Permeability before and after CIP operations.

only high precision instruments and protocols should be used in the future.

5.2. SDI/MFI testing

Silt density index was measured in a limited time period (23 August to 6 September), using the ASTM D4189 method, and results are shown along with the above shown turbidity measurements in Figure 10

The SDI value of the UF filtrate remains in the range of 2.5 to 3.2, with an average of 2.85 and a standard deviation of 0.15.

During the follow-up test (January to April 2009), more extended SDI and MFI testing was carried out. Below Fig. 11 shows the flow rate over the SDI filter for 17 tests over a time period of a month. The UF filtrate is from DOW™ Ultrafiltration module SFP-2860, as in the main study, operating at 75 L/h/m².

It can be seen that there is a relatively fast reduction in flow over the filter during the first 5 min. of the test, and later the flow stabilizes. This indicates that the flow loss is very fast in the beginning and much lower in the later period of the test. This indicates that SDI depends on test time, and that longer test periods yield significantly better SDI values – therefore the SDI is shown as function of test time in Fig. 12.

This data suggest that the flow loss in the SDI test is initially very variable and very high. Later, the value is far more stable and the reading is much more consistent, hence there is far less variation between the readings. Depending on the test time, values between 6.6 (5 min. test time) and 1.1 (45 min. test time) could be reported. It is unclear if this flow loss is really due to product water quality differences – stabilization effects of the filter,

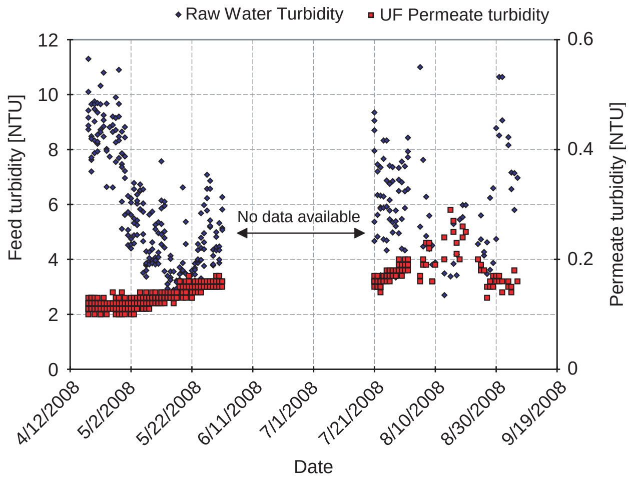

Fig. 9. Turbidity of feed and product water.

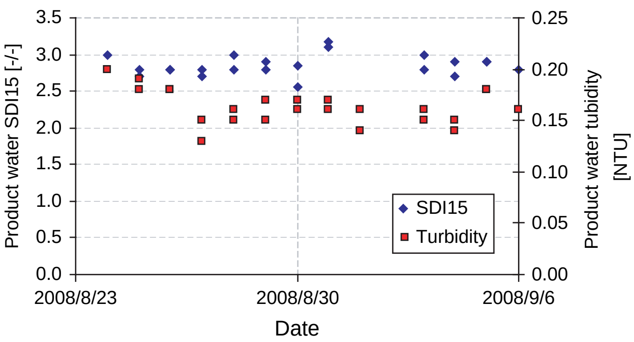

Fig. 10. Product water SDI15 (left axis, blue diamonds) and product water turbidity (red squares, right axis) in a limited time period.

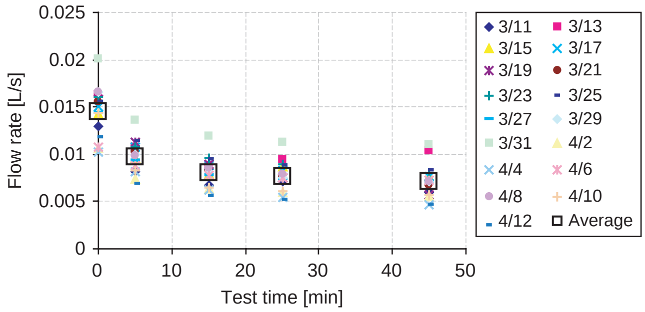

Fig. 11. Flow rates in SDI extended test.

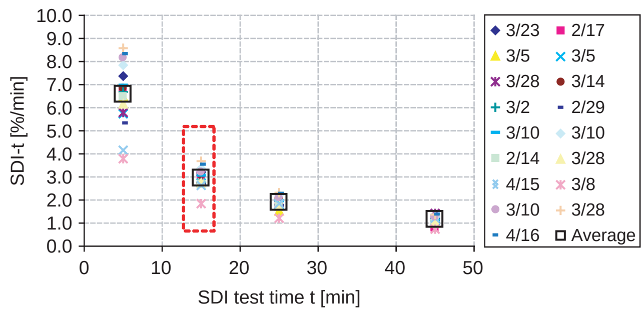

Fig. 12. SDI as function of test time.

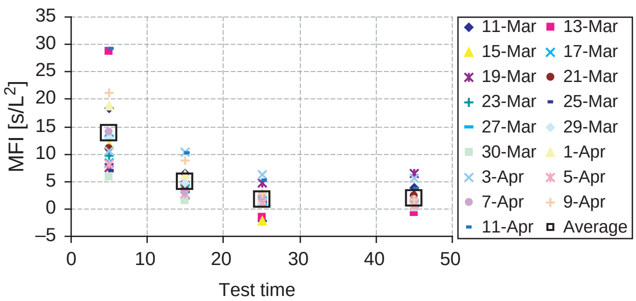

Fig. 13. Modified fouling index.

e.g. as function of salinity (Salinas et al., 2008) or due to pressure compaction might also play a strong role. If dominance of stabilization effects is confirmed, then the later readings would also be more accurate, which is the authors' opinion, but this will require more work.

MFI values for the different test times are also reported in Fig. 13, as a function of test time.

These values show also initially higher values (time period of 5 and 15 min.), but the 25 and 45 min readings show good comparable results and suggest that the readings are reliable. The average MFI based on microfiltration membranes is 1.9 s/L^2.

6. Summary and conclusions

A pilot study with outside-in pressurized PVDF ultrafiltration modules (DOW™ Ultrafiltration module SFP-2860) has been carried out in Qingdao. This study, mainly carried out from April 2008 to September 2008 focused on hydraulic aspects, such as different operational fluxes and cleaning protocols during four different test periods.

Based on a CEB interval of 12 h, operation at stable permeability (or TMP) was possible in a range of 60–85 $L/h/m^2$. At 110 $L/h/m^2$, permeability declined fast, which would suggest that such a high operation flux might require, despite the CEB frequency of 12 h, weekly CIP cleanings.

At 60 $L/h/m^2$, the CEB interval could be increased from 12 h to 120 h without adverse consequences. It also seems that the acid CEB is not required, or frequency could be significantly reduced. In the range of 80–85 $L/h/m^2$, it seems that the CEB frequency of 12 h is appropriate, and CIP might be required every four to six weeks.

Operation with and without air scrubbing shows that the cleaning effect of air scrubbing is significant. CIP operations based on a combination of oxalic acid, NaOH and NaOCl are successful in restoring permeability.

Water quality monitoring of the pilot test operation from April 2008 to September 2008, suggests that turbidity (measured with a lower precision device HACH 2100 P) remains below 0.2 most of the time, except during the test at 110 $L/h/m^2$, where it increases to 0.2–0.3. Product water SDI-15 is within a very narrow range (standard deviation of 0.15 %/min) around the average of 2.85 %/min.

Complementary water quality data during a follow-up test (January 2009 to April 2009) show significantly lower turbidity measurements of UF permeate, when a higher precision online device (HACH FILTERTRAK 660 sc) is used, which sheds doubt on the manual measurement with the low precision device. The complementing data also shows that 15 min might be a too short test interval for SDI, because the higher intervals show more reliable readings, in the range of 1.1 %/min. Calculation of MFI-MF from the data seems even more reliable – a value of 1.9 s/L^2 is found.

In conclusion it can be said, that outside-in pressurized ultrafiltration modules allow stable operation at high fluxes and with sustainable cleaning frequencies. The water quality reached is very good, but more work on the water quality measurement methods is required to fully demonstrate improvements from the 30 nm pore diameter ultrafiltration membranes, as compared with membranes having larger pore sizes and/or conventional media filtration.

Abbreviations

APHA – American Public Health Association
ASTM – American Standard Methods
AWWA - American Water Works Association
COD – Chemical Oxygen Demand
DBOO – Design Build Own Operate
MF - Microfiltration
MFI-MF – Modified Fouling Index using microfiltration membranes
NDF – Net Driving Force
NTU – Nephtelene Turbidity Units
PES – Polyethersulfone
PVDF - Polyvinylidene fluoride
TMP – Transmembrane Pressure
TOC – Total Organic Carbon
TSS – Total Suspended Solids
UF – Ultrafiltration
SDI - Silt Density Index
SWDP – Seawater Desalination Plant
SWRO – Seawater Reverse Osmosis

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