A pilot study of UF pretreatment without any chemicals for SWRO desalination in China

ARTICLE *in* DESALINATION · MARCH 2007

Impact Factor: 3.76 · DOI: 10.1016/j.desal.2006.08.006

Jia Xu
Ocean University of China

Guoling Ruan
Ocean University of China

Congjie Gao
Zhejiang University

Available online at www.sciencedirect.com
ScienceDirect
Desalination 207 (2007) 216–226
DESALINATION
www.elsevier.com/locate/desal

A pilot study of UF pretreatment without any chemicals for SWRO desalination in China

Jia Xu, Guoling Ruan*, Xizhang Chu, Ye Yao, Baowei Su, Congjie Gao
College of Chemistry and Chemical Engineering, Ocean University of China, Qingdao 266003, China
Tel. +86 (22) 8789-8199; Fax: +86 (22) 8789-8153; email: glruan@263.net

Received 13 January 2006; Accepted 9 August 2006

Abstract

The critical issue for a successful Sea Water Reverse Osmosis (SWRO) plant is pretreatment, which could provide consistent and high quality feed to SWRO membranes. In China, most pretreatment prior to SWRO use conventional ones, e.g. sand filtration, media filtration, cartridge filtration, et al, which have shown some drawbacks due to significant and unpredictable variation of seawater quality. For pretreatment of open seawater intake, membrane filtration may be a better choice. In this study, UF system utilizing hollow fiber membranes was used as pretreatment prior to SWRO desalination at Qingdao Jiaozhou Bay, the Yellow Sea in China. A different approach, focused on optimizing the design of a hybrid UF–RO system by maximum net product flow, i.e., an optimum correlation between filtration and backwash duration that can ensure best reliability of UF pretreatment was described. Operation of different recovery rate and flux of UF system was investigated to evaluate the performance of UF system. The results of the UF–SWRO system indicated that UF pretreatment could enable the RO pilot plant to be run stably and successfully. During the experimental periods, no chemical was injected into the UF–RO system, which showed that the UF–SWRO system performed well without any chemical cleaning.

Keywords: Ultrafiltration; Pretreatment; Seawater reverse osmosis; Desalination

1. Introduction

The world-wide concern of the vast scarcity of fresh water is rising day by day, due to the limited natural water resources. With the ever-increasing population and growing economy, demands for fresh water are continuously rising. Thus, many countries including China have devoted considerable effort to the field of seawater desalination.

Currently, reverse osmosis (RO) is one of the most prevalent methods for seawater desalination. However, a crucial drawback of RO membranes is their susceptibility to fouling due to the

*Corresponding author.

0011-9164/07/$– See front matter
doi:10.1016/j.desal.2006.08.006

presence of colloidal, particulate, dissolved organics and inorganic matter in feed water, as well as biological growth in the RO system. As a result, the sticking point for a successful SWRO plant is pretreatment, which can reduce the fouling potential of the feed-in seawater and provide consistently high quality feed to SWRO membranes.

Conventional pretreatment, based on mechanical filtration and chemical dosing systems, can be quite expensive. Mechanical filtration may consist of coarse screens, sand filters, media filters and micro cartridge filters. Dosage of a series of chemical products, such as disinfection agent (NaClO), flocculent agent ($FeCl_3$), chlorine scavenger agent ($NaHSO_3$) and anti-scaling agent (H_2SO_4), increase the cost and may be always in excess. Previous articles [1–3] have touched upon the problem of unstable quality and quantity of UF filtrate, both as the result of the unpredictable variation of the quality of raw seawater and imperfections such as leakages in the filters.

Advances in membrane technology and increasing requirements on water quality have stimulated the investigation and application of UF for SWRO pretreatment. UF membrane pretreatment can eliminate the need for cartridge or bag filters prior to RO system in cases where the UF permeate is fed directly to the RO system. UF technology has many advantages compared with conventional pretreatment process, such as:

- reduction of the overall dimensions of the plant and footprints
- absolute barrier to suspended particles, colloids, macromolecules, algae and bacteria
- consistent and high quality of product water independent of raw seawater quality
- simplicity of operation and maintenance
- easy automation
- less or no chemical consumption

The objective of this paper is to investigate the optimization of the design of a hybrid UF–RO system, based on maximum net product flow: an optimum correlation between filtration and backwash duration that could ensure best reliability of UF pretreatment. In addition, operation of different recovery rate and flux of UF system and performance of SWRO were also investigated to evaluate the reliability of UF pilot plant.

2. UF–RO experiments

2.1. Features of the UF and RO membrane systems

The UF system which has a maximum production capacity of 28 m^3/d was tested on local seawater in Qingdao Jiaozhou Bay, the Yellow Sea of China. The UF membrane system is arranged in 2 trains, each housing 3 modules. The design criterion of the project was to ensure a continuous and safe operation, and to meet the technical requirements of the product water quality and quantity. The UF membrane has a hollow fiber configuration with an ID of 0.6–1.0 mm and OD of 1.3–2.0 mm. It is manufactured from Tianjin, China and made of PAN with a maximum operational pressure of 0.3 MPa. It has a nominal pore size of 0.02 μm (50,000 MWCO) with a total effective surface area of 30m^2. Cross-flow filtration was adopted during the experiments with the UF filtrate flowing inside the hollow fibers (outside-in mode). Frequently backwash of UF was performed to maintain a stable permeate flow rate by physically removing the fouling layer from the UF membrane surface. Membrane operation which include on-off of the UF–RO system, backwash and in-situ cleaning procedures when needed, are fully automated and controlled by a programmable logic controller (PLC).

RO membranes of composite polyamide material were used in the experiments. Characteristics of the membranes are shown in Table 1.

2.2. Process of UF–RO systems

The process flow diagram of the UF–RO pilot

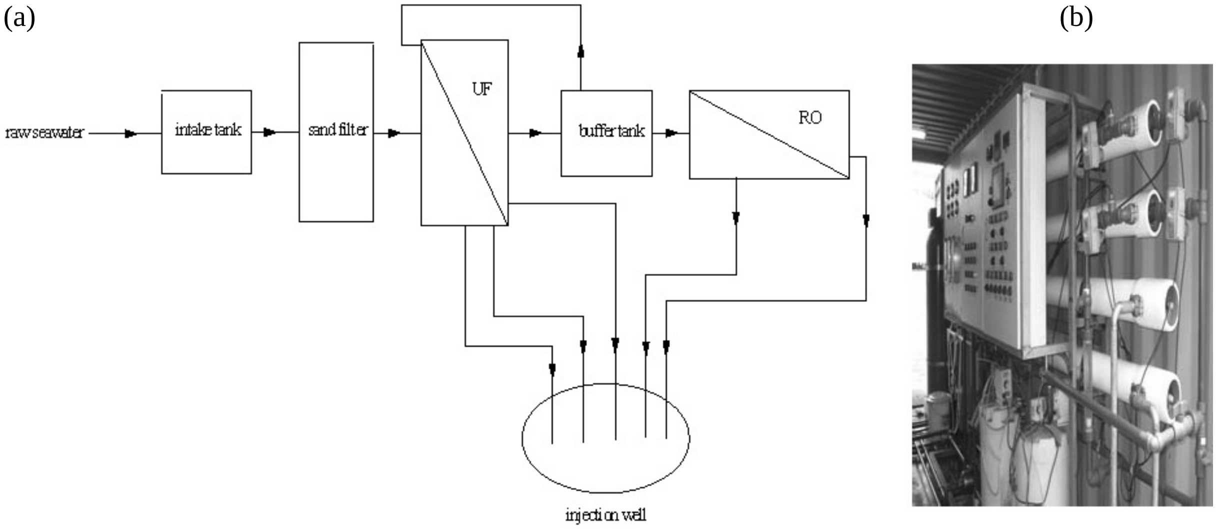

Fig. 1. The UF–RO pilot system. (a) Schematic diagram of the pilot system. (b) Photo of the pilot system.

Table 1
Characteristics of RO membranes

Parameter	RO membranes
Membrane element	SWC1-4040
Type configuration	Spiral-Wound
Membrane polymer	Composite
Salt Rejection, %	Polyamide
Minimum recovery for any	99.5
element, %	10
Permeate flow for any element, L/h	187.5
Maximum applied pressure, MPa	6.9
Maximum pressure drop for each element, MPa	0.07

system is shown in Fig. 1. Raw seawater was first disposed by a cartridge sand filter to provide feed water for UF system, and the UF filtrate is further pumped to RO system. All water sources such as UF concentrate, UF backwashing waste, RO permeate and concentrate etc. were collected and rejected back to the see via the injection well on site.

The cartridge filter was made of stainless steel, with an OD of 0.5 m and height of 2.5 m.

Table 2
The operation parameters of sand filter

Parameter	Sand filter
Type	180-F-1665
Filtration flow rate, L/h	2200–3000
Filtration intervals, s	60
Filtration duration, min	60
Backwash flow rate, L/h	2500–3000
Flocculants used	no

The effective sand height was 1.8 m. The operation parameters of sand filter that could remove more than 20 μm particles in the raw seawater are shown in Table 2.

2.3. Experimental procedure

2.3.1. Optimization experiments on the filtration and backwash duration, and backwash flow rate of UF pilot system

In this optimization experiment enacting that backwash flow rate is twice as much as that of UF filtrate, the operational pressure of UF was 0.1 MPa, and filtration duration varied from 20 to

90 min. Backwashing was performed using UF permeate and lasting from 10 to 45 s under pressure of 0.2–0.25 MPa. Four strings of experiments were carried out in all. In each string with selected backwash durationτ, different filtration durations were tested to evaluate the most effective value of based on maximum net product flow. Therefore, both of the overall product volume and backwash water volume were determined. In the first string of experiments, τ was fixed at 45 s and t was fixed at 20, 40, 60, and 90 min, in turn. In the second, third and fourth string of experiments, τ as fixed at 30 s, 20 s, and 10 s, respectively, and the values of t took the same as the first string of experiments.

With the optimized τ and t, the optimum flow rate of backwash was investigated. The ratio of backwash flow rate to that of UF permeate was tried on the values of 1.5, 2, 2.5 and 3 to evaluate the efficiency of backwash for the reliability of UF.

2.3.2. Performance of UF under different operating conditions

In this section, rejection characteristics and performance consistency of the UF pilot system were evaluated under different operating conditions which included high recovery-high flux, high recovery-low flux, low recovery-high flux, and low recovery-low flux. In all pilot studies, no chemicals were injected into the UF–RO system whether through the feed water or the backwash water.

2.3.3. Performance of RO pilot system

The main aim of this section was to appraise the stable functioning of the RO pilot plant under its designed operating conditions with the variation of UF system operations. The data of permeate flow, transmembrane pressure (TMP), feed temperature, conductivity and pH of permeate were recorded.

3. Results and discussion

3.1. Optimization experiments

Regular backwash can destroy the accumulated foulant layer which diminishes the active membrane surface. The backwash frequency may vary from 20 min to every few hours depending on the system and the feed-water quality [3]. The efficiency of regular backwash depends on backwash duration τ, filtration duration t, and backwash flow rate. By keeping the values of τ approximately constant during the experiment, it can be observed that UF permeate flow decreases with filtration duration, which indicated that the longer the filtration duration, the stronger the accumulated foulants. However, backwash water volume decreases with filtration duration. Thus, the cost-oriented optimization of UF plant design requires the selection of an appropriate values of τ and t, based on maximum net product flow which is determined as the difference between the overall product water collected and the backwash water required [4,5].

The product flux of UF system of each string of experiments is shown in Fig. 2. It could be seen that a drop of product flux of UF system with time in the first string of experiments (conditions: backwash duration τ= 45 s). When filtration duration equaled 20 min (Fig. 2a), the flux declined from 60 l/m^2h to 56.8 l/m^2h, with drop rate of 5.3%. As filtration duration was increased up to 40 min (Fig. 2b), the flux declined from 60 l/m^2h to 54.8 l/m^2h, with drop rate of 8.7%. And the drop rate of the flux was 10% and 14.2%, respectively, when filtration duration was 60 min (Fig. 2c) and 90 min (Fig. 2d). Accordingly, a skin-deep and obvious conclusion can be obtained that with the extending of filtration duration, the drop rate of flux augmented. That is, the longer the filtration duration, the less the product water that UF system could produce in the same experimental duration. However, the volume of backwash water would

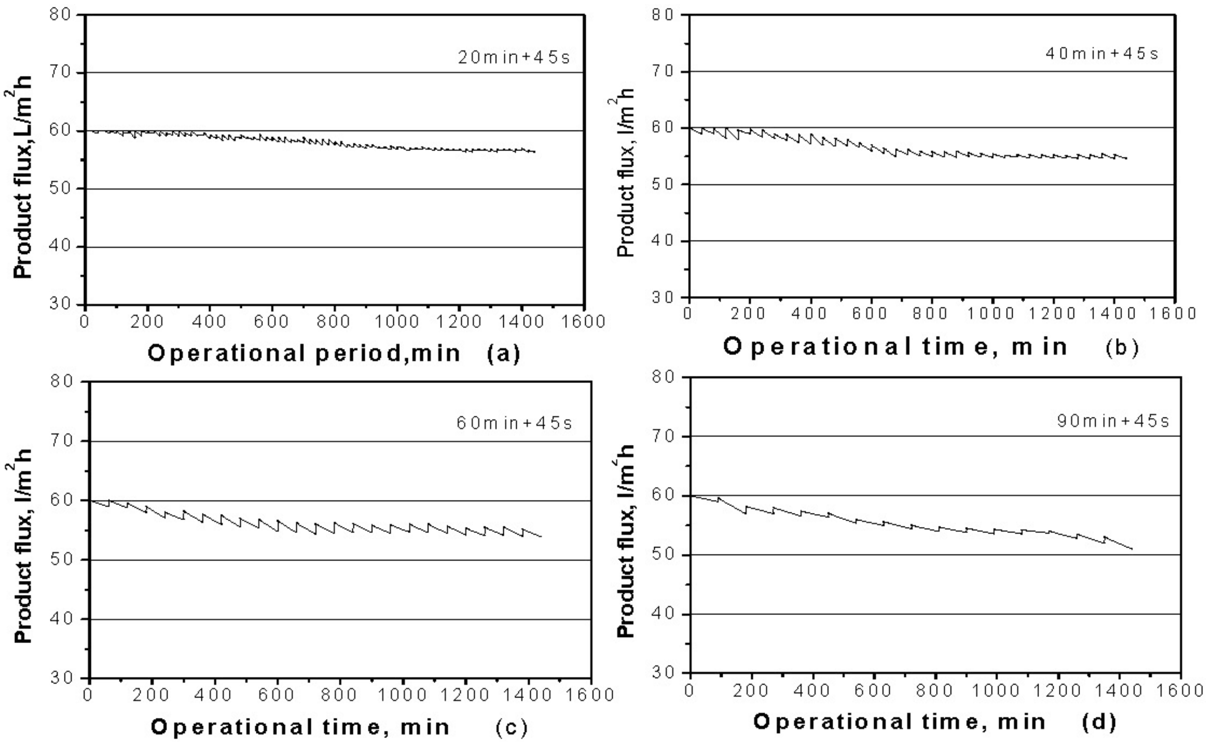

Fig. 2. Product flux of UF system vs. time (backwash duration τ = 45 s). (a) filtration duration = 20 min; (b) filtration duration = 40 min; (c) filtration duration = 60 min; (d) filtration duration = 90 min.

decrease with the filtration duration, which demonstrated that with the extending of filtration duration, product water of UF system as backwash water was reduced and more water could be used as the feed to SWRO. Therefore, the maximum net product water, i.e., the water as feed to RO, expressed as the difference between the overall product water collected and backwash water required [4,5] depends on filtration duration t and backwash duration τ.

The overall values of product volume can be obtained by the above plots of product flux. And the volume of backwash water in each experiment can be calculated according to the following equation:

$$V_b = \frac{F_b T \tau}{60t} \tag{1}$$

where V_b and F_b represent the overall backwash volume required and the backwash flow during the backwash duration τ, and T represents the total experimental duration (min). Then, the volume of net product water can be obtained. Fig. 3(a) shows the variation of volumes of overall product water and net product water with filtration duration for the case when backwash duration lasted 45 s. Plotted in Fig. 3(a), the volume of overall product water decreases with filtration duration, but the volume of net product water has a peak value under the condition (t = 60 min), which demonstrated that the optimum filtration duration value was determined in the first string of experiments. In conformity to this optimization method, optimum filtration duration value of other three strings of experiments can be also obtained. Fig. 3(b) presents the four curves

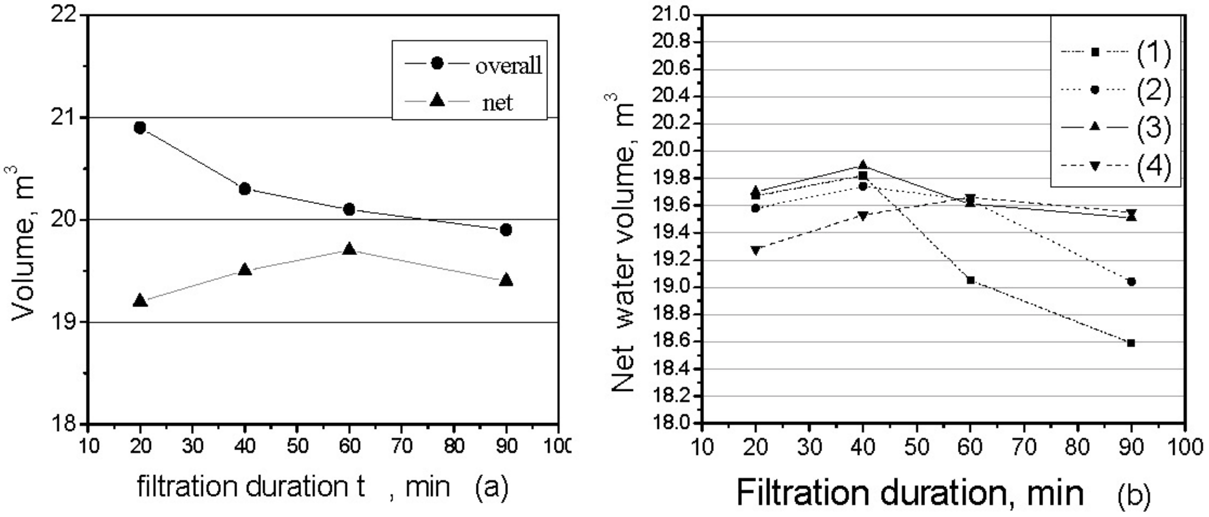

Fig. 3. (a) Overall product water and net product water with different filtration duration (τ = 45 s); (b) Net product water with different filtration duration in the four strings of experiments; (1) τ= 10 s; (2) τ = 20 s; (3) τ= 30 s; (4) τ = 45 s.

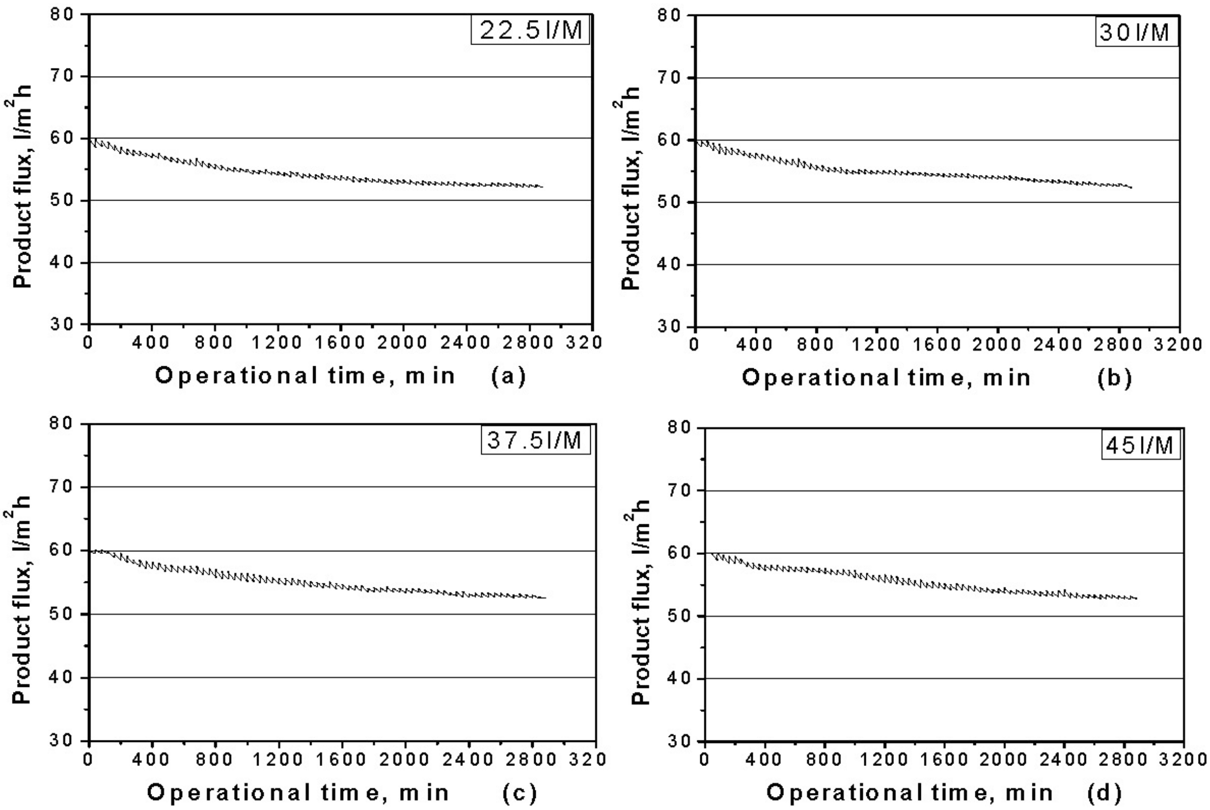

Fig. 4. Product flux of UF with different backwash flow rate. (a) flow rate of backwash 1350 l/h; (b) flow rate of backwash 1800 l/h; (c) flow rate of backwash 2250 l/h; (d) flow rate of backwash 4700 l/h.

that yielded dependencies of the product volume on filtration duration of the four experiment strings. The optimum condition (durations of filtration and backwash were fixed 40 min, 30 s, respectively) was acquired from Fig. 3(b).

Based on the above selected filtration and backwash duration, the selection of the optimum flow rate of backwash was conducted. The ratios of flow rate of backwash to that of UF permeate were tried on the values of 1.5, 2, 2.5 and 3 to evaluate the efficiency of backwash for the reliability of UF. Product flux of UF with different selected flow rate of backwash (1350 l/h, 1800 l/h, 2250 l/h and 4700 l/h, respectively) is shown in Fig. 4. During each experimental (50 h), the flux declined from 60.0 to (a) 52.2 l/m^2h, (b) 52.4 l/m^2h, (c) 52.5 l/m^2h and (d) 52.8 l/m^2h, whose drop rate was 12.67%,12.0%,12.0% and 11.33%, separately. From these data, a conclusion could be drawn that the flow rate of backwash played a less important role in influencing the efficiency of backwash for the reliability of UF due to less obvious difference of UF product flux with different flow rates of backwash. Still, compared with the other three flow rates of backwash, the effect of value of 1800 l/h was most efficient. The product flux of (a) was lower. As to backwash system of (c) and (d), net product water of UF reduced greatly due to the augment of volume of backwash water though product fluxes were higher. Therefore, 1800 l/h was the optimum flow rate of backwash with regard to this pilot test.

3.2. Performance of UF under different operating conditions

In order to study the operation of the UF pilot plant, various conditions including high recovery-high flux (80%, 72 l/m^2h), high recovery-low flux (80%, 60 l/m^2h), low recovery-high flux (50%, 72 l/m^2h), and low recovery-low flux (50%, 40 l/m^2h) were tested during the experimental periods. The results are presented in Fig. 5(a) and (b).

As shown in Fig. 5(a), decline of flux of UF pilot plant was evident under the condition of higher flux (72 l/m^2h), no matter which level of recovery (50%, 80%) selected. Comparatively, flux of UF under the condition of lower flux (60 l/m^2h and 40 l/m^2h) declined more slightly during the experimental periods. Under the condition of higher recovery (80%), feed water can be used to a larger extent. Moreover, the operating efficiency in cross-flow mode and maximal volume of filtrate water can meet the optimum function at the same time. So, low recovery operation was not advisable due to small volume production in despite of the stable flux. As Fig. 5(b) shows, all the TMP and feed pressure trends increased in the experiments due to the foulant accumulation on the membrane surface, which signified that stable performance was not sustainable. Moreover, the variation of TMP and feed pressure of high recovery-high flux (80%, 72 l/m^2h) operation was highest among all the operations, which led to a rise of energy consumption. Thus it can be seen that backwash of UF was not totally effective to remove cake layer, and the UF pilot plant needs a chemical clean when the rise of TMP exceeds 15%. To sum up, high recovery-low flux (80%, 60 l/m^2h) working principle might be adopted.

Parameters including conductivity, total dissolved solids (TDS) and chemical oxygen demand (COD), total suspended solid (TSS), SiO_2 (reactive) and pH were analyzed to evaluate the quality of raw seawater, filtrate of sand and permeate of UF, as shown in Table 3. From the chemical analyses performed, due to tiny difference of the quality between raw seawater and filtrate of sand, sand filters might be not necessary before the UF pilot plant.

Apart from chemical analysis above, the Silt Density Index (SDI) and turbidity were recorded for long periods to track the performance of the UF system. SDI is an empirical test developed for representing the potential for fouling of the membranes by finely suspended particles present

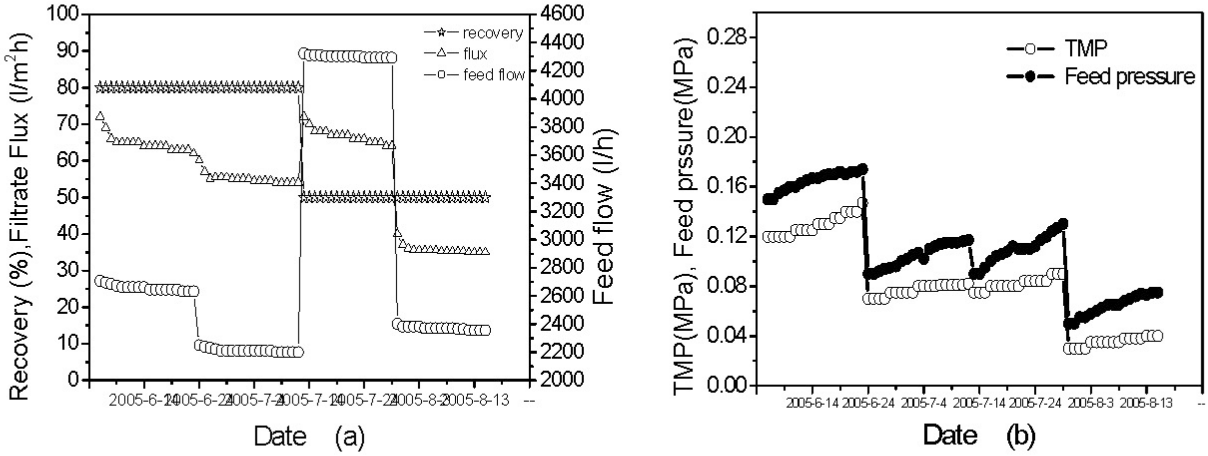

Fig. 5. Parameters of UF under various conditions. (a) Recovery, flux and feed flow of UF. (b) Feed pressure and TMP of UF.

Table 3
Results of chemical analysis of UF pilot

Water	Raw seawater	Sand filtrate	UF permeate
Conductivity, µS/cm	39000–47680	39800–45920	38000–42000
TDS, mg/L	26000–30120	26000–28820	20800–25520
TSS, mg/L	4.8–8.9	3.8–7.3	1.1–2.1
SiO_2 (reactive), µg/L	363–897	378–899	337–862
pH	7.82–8.05	7.80–8.03	7.85–8.03
COD, mg/L	1.15–1.76	1.15–1.76	0.87–0.96

in feed water to the membranes. The procedure is based on the time required to filter a volume of feed water through a 0.45 micron filter paper at a feed pressure of 30 psig at start and then after 5, 10 and 15 min of continuous filtration. The procedure is ASTM standard test method D 4189-82. Usually SDI_{15} was used, however, for high TSS water such as seawater, SDI_5 was used. Turbidity was measured by a turbidity meter (LP2000-11, Hanna, Italy). The trends of turbidity and SDI are presented in Fig. 6(a) and 6(b) respectively.

From the data in Fig. 6(a), turbidity of raw seawater, sand filtrate and UF permeate varied in the range of 3.0–27.0 NTU, 0.5–25.0 NTU and 0.00–0.01 NTU, respectively. During Aug. 5th to Aug. 10th, very high turbidity peaks of raw seawater appeared unconventionally due to a heavy storm which made the quality of seawater degraded. And, it can be found that values of turbidity of the sand filtrate were even higher than those of raw seawater in these days, which was abnormal. It indicated that the sand filter prior to UF system was fouled seriously so that it cannot remove particles from raw seawater efficiently. The values of SDI_5 of raw seawater were above 15.85 and most of most of them could not be tested in many cases, so were those of sand filtrate. However, the UF system can still stand the degraded feed water. The quality of UF permeate was excellent with 100% of turbidity

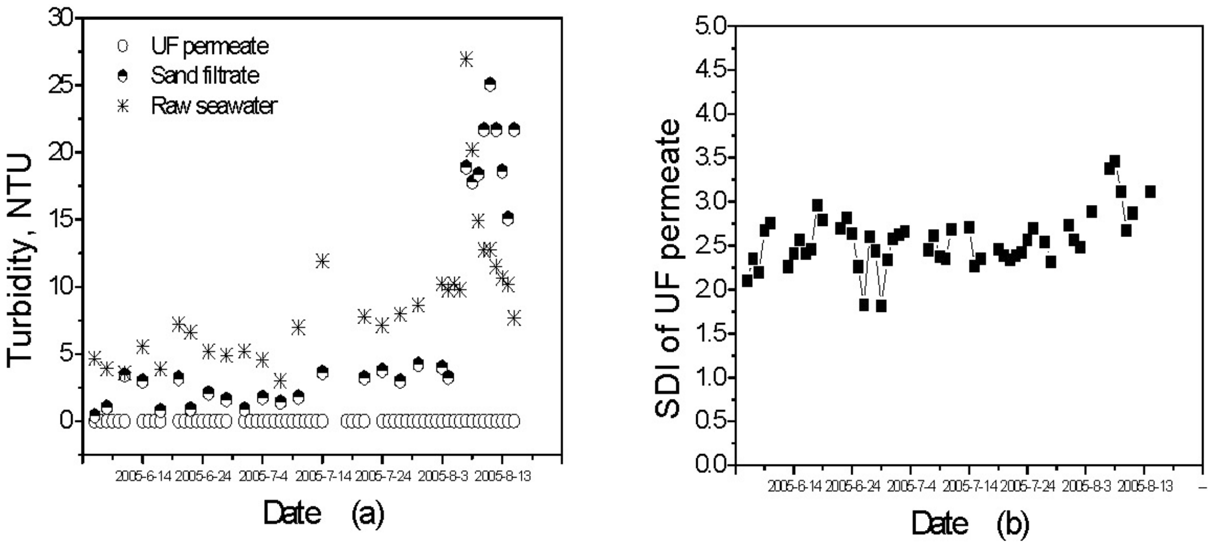

Fig. 6. (a) Turbidity of raw seawater, sand filtrate and UF permeate. (b) SDI trend of UF permeate.

measured below 0.01 NTU and 95% of the SDI_{15} below 3.0 (Fig. 6(b)). Even through the worst periods, the values of SDI_{15} were also no more than 3.5, which can satisfy the need of RO feed water.

3.3 Performance of SWRO based on the UF pretreatment

The UF pretreatment could enable the SWRO pilot plant to be run at stable TMP and recovery. SWRO was run on UF filtrate without cleaning. The SWRO system performance data is shown in Fig. 7(a). TMP was in the range of 5.45–5.60 MPa and maintained stable during the experimental time, which indicated that the RO membrane was not fouled or fouled slightly. However, there was a apparent increase in permeate flow and recovery. The phenomenon that permeate flow increased from 7.4 to 11.0 m^3/d is mainly due to the increase of feed temperature, as shown in Fig. 7(b), which had a crucial effect on the permeate flow. With the experiment carried on, temperature of raw seawater was becoming higher and higher (from 14 to 20°C), so was the feed temperature of SWRO (from 15 to 25°C). The feed seawater with higher temperature has higher diffusion coefficient and lower viscosity, so that the permeate flow increased. However, the standard permeate flow was obtained by TCF (temperature calibration factor) in order to investigate the stability of RO permeate without the influence of the feed temperature, as Fig.7(a) shows, whose results made clear that RO permeate flow did not decline. The TCF can be calculated from the following equation:

$$TCF = \exp\left(K^*(1/(273+t) - 1/298)\right) \qquad (2)$$

where TCF represents temperature calibration factor, K represents constant of membrane material; t represents feed water temperature.

Other parameters, such as pH and conductivity of RO permeate, were also analyzed, as shown in Fig. 7(b). The values of pH maintained in the range of 6.6–6.8. However, conductivity was unstable, especially during July 14th–July 17th. The peak of conductivity may be contributed to the pause of RO system for five days. But it

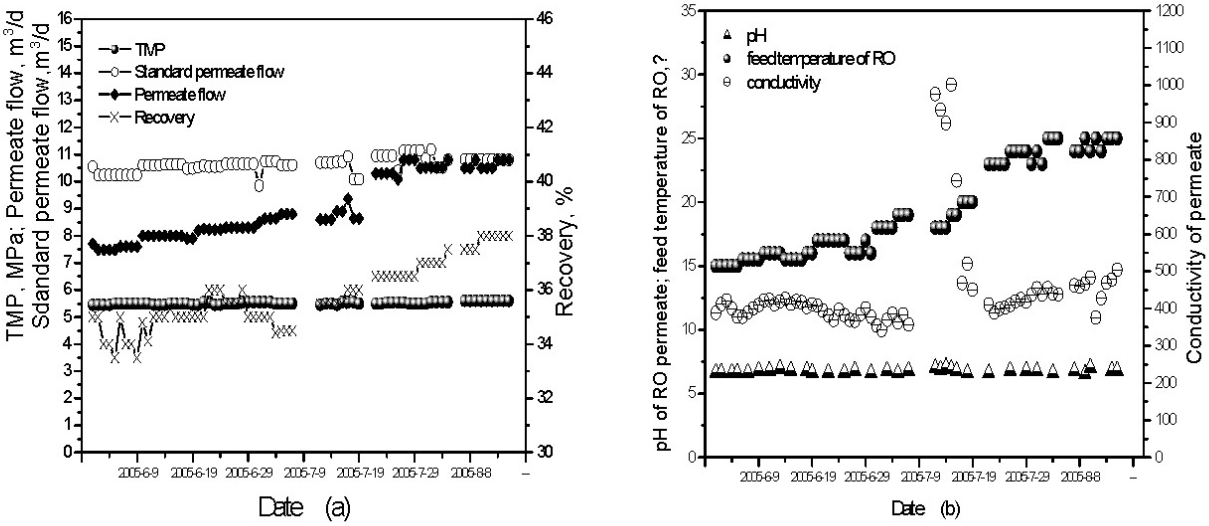

Fig. 7. (a) TMP, permeate flow and recovery trends of RO pilot plant. (b) Water quality of RO permeate.

began to get right after several days, and was in the range of 350–500 μS/cm, which was still slightly higher than the initial values of conductivity. This might be caused by the effect of the increasing temperature on salt transport, for the diffusion of the salt increases with the temperature.

4. Conclusions

Based on the results obtained in the present study, conclusions can be drawn as follows:

- Performance of the UF system is excellent with the following optimum backwash parameters: backwash duration $\tau = 30$ s, filtration duration $t = 40$ min, and backwash flow rate is 1800 l/h.
- The operation of the UF system in high recovery–low flux mode (80%, 60 l/m^{2}h) might be the best and should be adopted.
- The quality of UF permeate was very good, with 100% of turbidity below 0.01 NTU and 95% of the SDI_{15} below 3.0, which can totally satisfy the need of SWRO feed water.
- Performance of the SWRO system is excellent with a stable TMP of averaged 5.5 MPa and stable calibrated permeate flow. The conductivity of RO permeate was in the range of 350–500 μS/cm.
- During all the experimental periods, the UF–RO system can be run safely and successfully, without any chemicals required for disinfection, flocculation, enhanced chemical back wash (CEB) and cleaning.

Acknowledgements

The authors would like to express their appreciation to the Institute of Seawater Desalination and Multipurpose Utilization, SOA (Tianjin) and Huangdao Power Plant in China for their contribution in the success of the pilot tests. The work was financially supported by the National Science Foundation of China (No. 20506025).

References

[1] K. Chida, Reverse osmosis plants operation and maintenance experience in the Middle Eastern region, Desalination, 110 (1997) 59–64.

[2] M. Wilfand and M.K. Schierach, Improved performance and cost reduction of RO sweater systems using UF pretreatment, Desalination, 135 (2001) 61–68.

[3] A. Brehant, V. Bonnelye and M. Perez, Comparison of MF/UF pretreatment with conventional filtration prior to RO membranes for surface seawater desalination, Desalination, 144 (2002) 353–360.

[4] A.G. Pervov, E.V. Dudkin, N.B. Motociloca and A.P. Andrianov, Ultrafiltration-technology of the future. Water Supply Sanitary Tech., 9 (2001) 9–12.

[5] A.G. Pervov, A.P. Andrianov, R.V. Efremov, A.V. Desyatov and A.E. Baranov, A new solution for the Caspian Sea desalination: low-pressure membranes. Desalination, 157 (2003) 377–384.