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Study on different ultrafiltration-based hybrid pretreatment systems for reverse osmosis desalination

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HIGHLIGHTS

- Ultrafiltration (UF) is a promising pretreatment method for Reverse osmosis (RO).
- Controlling the membrane fouling of UF is a major research focus.
- Flocculation and sand filtration pretreatment technology were studied.
- The attenuation of specific flux (SF) of UF was analyzed.
- Water analysis was performed to quantify the pollutants removal performance.

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ABSTRACT

Performance of different pretreatment systems with ultrafiltration (UF) prior to reverse osmosis (RO) for desalting seawater was assessed in this paper. The pilot trial was operated on seawater from Bohai Bay in Tianjin using polyvinylidene fluoride (PVDF) hollow fiber UF membrane. During these experiments, membrane specific flux (SF) was calculated to evaluate the performance of UF. Results of the research showed that in a chemical enhanced backwash (CEB) period, the combination of UF with $FeCl_3$ flocculation pretreatment was helpful in controlling the decrease of SF during the operation. Besides, the result also showed that $FeCl_3$ flocculation/dual-stage sand filtration/UF performed effectively in terms of the stable of SF in a CEB period than $FeCl_3$ flocculation/UF alone. In addition, water analysis was regularly performed to quantify pollutants in the effluents of different hybrid processes. According to the experiment, UF can provide product water with consistently low turbidity (0.07–0.12 NTU) and low silt density index (SDI_{15} less than 2) levels regardless of seawater quality. Sand filtration showed good performance for turbidity removal (less than 0.5 NTU in effluent), but limited effect on SDI removal (not below 4). Total organic carbon (TOC) removal up to 28% was obtained in $FeCl_3$ flocculation/dual-stage sand filtration/UF hybrid system.

1. Introduction

The shortage of fresh water has become a prominent problem to limit the development in many parts of the world. As an effective technique for drinking water production, seawater reverse osmosis (SWRO) desalination has found wider applications in solving this problem due to its improvements in cost-effectiveness and breakthroughs in membrane performance in the last decades [1–3]. (The use of polymeric materials has largely solved the chemical degradation problem experienced by cellulose acetate membrane in the early days). However, the surface of RO membrane is subject to fouling by foreign materials in the feed solution such as calcium precipitates, organics, hydrates of metal oxides, and biological matter. The performance of the RO process can be significantly affected by the membrane fouling, which is specifically manifested in a lower permeate flow rate, increased transmembrane pressure (TMP), and high solute passage. Besides, another issue of concern is that the suspended particles in the feed solution could plug the brine spacers of the RO module during the operation. The practical operation of RO membranes requires the silt density index (SDI_{15}) of feed water not more than 3.0 to minimize the membrane fouling [4]. So a stable and effective pretreatment system is very important for the successful operation of a SWRO desalination plant, especially in the areas with poor-quality seawater.

Conventional antifouling strategies have been widely used for SWRO system, such as flocculation, clarification (gravity, or dissolved air flotation) and cartridge filters. But they still have some deficiencies in practical applications now. On the one hand, the conventional pretreatment method cannot meet the high quality demand of feed water for RO,

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which will probably lead to the poor running stability, low flux and frequently cleaning of RO unit during the operation. On the other hand, the conventional pretreatment process is relatively cumbersome so that the investment cost and energy consumption are comparatively high. Instead, membrane technology quickly adopts the role of the innovator. UF has fast been accepted as the preferred pretreatment to SWRO [5]. The UF membrane has small tortuous pores, with pore diameters smaller than 0.10 μm which enable it to perform effectively in removing the suspended particles and colloids in seawater. In recent years, pilot-scale installations of UF have grown up due to the reliability of these processes for producing superior quality feed to RO.

A successful UF system has to perform well in terms of filtrate quality and stable operation (stable flux and stable trans-membrane pressure (TMP)). Unfortunately, during the foulants retaining process, UF membrane would also suffer from severe membrane fouling [6], mainly associated with the colloidal materials. These colloids may agglomerate and adhere to the membrane surface and lead to the formation of cake layer. Moreover, colloids may also be cross-linked with materials like organic or inorganic polymers and become gels to plug pores. Then the TMP would be increased, and membrane cleaning and replacement would become more frequently. Therefore, the operating cost will be increased.

Therefore, in consideration of the severe fouling problem and the long-term operation cost, integrated process that comprises conventional technology and UF is the reasonable option in improving pretreatment effect for RO. Numerous studies have been conducted in this area [7,8]. Van Hoof et al. [9] set up a pilot plant in Trinidad to validate the hollow fiber UF technology as an appropriate pre-treatment method to ensure optimum performance of RO systems. The UF operational data and estimated costs were taken into consideration. It was indicated that the backwashing performance would be improved with the addition of pre-coagulation prior to UF process. Halpern et al. [10] discussed two pilot studies which were operated on deep basal well and surface water with an open intake respectively, proved hollow fiber UF membranes can provide superior quality feed to RO regardless of seawater quality. Brehant et al. [11] proposed that the combination of UF with a conventional coagulation with ferric chloride helped in controlling the UF membrane fouling and providing consistently high quality water in steady state conditions. Hyun-Jin Yang and Kim [12] studied the effect of pre-coagulation on MF/UF as a pretreatment for reverse osmosis (RO) in seawater desalination, discussed the effect of coagulant dose and pH in the coagulation–membrane filtration system. It proved that the combination of membrane filtration with pre-coagulation was more effective than membrane filtration alone. Chua et al. [13] presented the performance of four pretreatment systems utilized in the RO desalination systems. According to the results of the pilot trials in Singapore, UF can produce high quality filtrate with a SDI value below 3.0 while using sand-filtered seawater as the feed water. Gao, C et al. [14] conducted the experiments at Huangdao power plant (Jiaozhou Bay of Yellow Sea, China) to evaluate the performance of a ceramic UF membrane system in pretreatment to seawater desalination. Cui, Z et al. [15] set up a pilot plant to study the ceramic membrane pre-treatment for seawater desalination with reverse osmosis in Tianjin Bohai Bay, China.

The Bohai Sea is China's continental sea. Two of China's most populous cities, Beijing and Tianjin, are both near the Bohai Gulf. Right now, this economically dynamic area is faced with serious crisis of water resource as its economy grows. Urban water conservancies may not be able to meet the rising water demands by the industry and urban life. The state encourages and supports seawater desalination in the coastal area of Bohai as an effective method to solve water crisis. As Chinese government continuously putting forward the new plans to develop the desalination industry in this area, research on the pretreatment system gains more far-reaching significant. However, the study on the RO pretreatment system in Bohai area is still insufficient, especially under the operating condition in winter. Also the use of multi-stage pretreatment system (flocculation/sand filtration/UF) has not been studied in this area before. This study is as the basis of research for finding an effective pretreatment system based on hollow fiber UF membrane for RO desalination in the future in the Bohai Sea of China. Hybrid pretreatment systems were studied in this pilot-scale experiment: (1) UF alone, (2) flocculation/UF, (3) sand filtration (coarse/fine/dual-stage)/UF, and (4) flocculation/sand filtration (coarse/fine/dual-stage)/UF. The performance of these systems was estimated in the test, and the effluents from different hybrid processes were periodically analyzed.

Table 1
Characteristics of seawater.

Parameters	Range
Temperature (°C)	5–15
pH	7.95–8.35
Turbidity (NTU)	1.6–7.0
Conductivity (mS/cm)	44.8–46.5
UV254 (m^{-1})	0.0397–0.0550
COD (mg/L)	1.32–2.64
TOC (mg/L)	3.64–5.16
SS (mg/L)	4.13–13.60
Fe (mg/L)	0.0238–0.1600
Mn (mg/L)	0.002–0.005
Si (mg/L)	0.2490–0.4365

2. Materials and methods

2.1. Seawater and flocculants

The pilot experiment was carried out in Tianjin Lingang Economic Development Zone. Seawater from Bohai Bay with a TDS value ranging from 29 g/L to 32 g/L was used. The characteristics of seawater are outlined in Table 1.

Ferric chloride ($FeCl_3 \cdot 6H_2O$) was used as flocculants in this study. A previous lab-scale test experiments have been carried out to examine the optimum dosage of flocculants, results of which show that 3–6 ppm dosage proves the most obvious effect.

2.2. Sand filtration system

Plexiglas columns packed with two kinds of sand were used in this pilot trial. Parameters of sand filter are shown in Table 2.

Filtrate flow of 2.2 m^3/h for sand filtration was adopted during the operation. Air & water backwashing was performed every one to two days (according to the pressure drop) in this experiment to eliminate the plugging of the filters caused by the retained particulates. Operating conditions of the sand filtration are presented in Table 3.

2.3. UF pilot

The overall experiment was conducted using an PVDF hollow fiber membrane (UOF-4D, MOTIMO, China). Table 4 presents the parameters of the UF membrane used in this study.

Membrane cleaning processes were performed periodically in this experiment to eliminate the membrane pollution and renew membrane flux. Operating conditions including the interval and duration of backwash or the dosage of chemicals when performing CEB were optimized through the previous test operation. The details about the operating conditions of UF are presented in Table 5.

Table 2
Parameters of sand filter.

	Coarse sand filter	Fine sand filter
Average particle size (mm)	0.8–1.0	0.35–0.5
Inside diameter of column (m)	0.5	0.5
Height of column (m)	1.5	1.5
Depth of filter media (m)	1.0	1.0