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Adaptability of ultrafiltration and its pretreatment process in three types of feed water

Huiming Zeng[a], Jingdong Zhang[b,*], Chunsong Ye[a], Jiuyang Lin[a]

[a]*Department of Water Quality Engineering, School of Power & Mechanical Engineering, Wuhan University, Wuhan 430072, People's Republic of China*
[b]*School of Safety Science and Administration, Zhongnan University of Economics and Law, Wuhan 430073, People's Republic of China*
Tel. +86 27-68772266; email: weimingzeng@tom.com

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ABSTRACT

In order to get the best performance of ultrafiltration (UF) process in the pilot test, this paper chooses the appropriate coagulant for coagulation process used as the pretreatment of UF process, investigates the key influence factor of coagulant dosage, membrane fouling and permeability, and proposes a method to optimize the operation parameters of UF process. In this study, UF module is fed with three different types of raw water to verify the adaptability of UF membrane. The results indicate that polymer ferric sulfate (PFS) is the appropriate coagulant for low temperature seawater due to its economical efficiency and good coagulation performance, and the content of the silica in the raw water is the key influence factor of coagulant dosage. During the UF process, the UF membrane module (SXL-225 FSFC) could offer the permeate of stable quality characterizations, which meets the feeding requirement of RO. But the key influence factor of the membrane fouling is not the temperature but the components of feed water, especially the content of silica and other colloids.

Keywords: UF; adaptability; Coagulation; Operation parameter

1. Introduction

As the development of industry, the fresh water resource becomes more and more inadequate due to the increasing of population and regional distribution imbalance of water in China. Nowadays, people produce the fresh water by seawater desalination or wastewater recycling through a series of methods. Ultrafiltration, the low pressure membrane process, has drawn more and more attention in recent years and has been increasingly used in water treatment as an alternative technology to the conventional filtration process such as sand filtration, and activated carbon filtration, to remove suspended particles, colloids and microorganisms. During the last decade, it is reported that the membrane process has increasingly applied in the fields of domestic sewage and industrial wastewater treatment.

One of the crucial issues that represent an important limitation to UF process is membrane fouling, which severely influence the cost-effective performance and life span of the UF membrane. Significant efforts to identify predominant membrane fouling mechanisms (i.e. adsorption, pore blockage, and gel formation) have been conducted. And many pilot scale and lab scale observations focused on single component in surface water are completed to study the fouling mechanism and prediction of irreversible membrane fouling.

*Corresponding author.

Decarolis [1] demonstrates the effect of membrane operating flux and backwash conditions on the performance of a pilot test of UF membrane for surface water treatment. Jiang *et al*. [2] carries out a similar study on the pilot test of a membrane bioreactor and sets up a mathmematical model to predict the membrane fouling. Although some of the mathematical models can predict some results of membrane fouling when actual surface water is used as the raw water, it is limited to adapt to the other types of feed water of different water quality characterizations because of complex components in the feed water.

In order to apply the membrane module successfully and get the optimal operation parameters of membrane in the full-scale process, it is necessary to carry out the pilot test or laboratory scale test due to the lack of standard method or technical regulations. In this study, a pilot test of UF process is carried out to set up an adaptable coagulation process, select a proper type of membrane module for the feed water with fixed water quality, and get the optimal operation parameters of UF process.

2. Materials and methods

2.1. Source water

In the pilot test, the three types of feed water samples are tested, the first type of feed water sample comes from the Yueqing Bay in Eastern Sea, the second type comes from the Bohai bay, and the third type is the cooling tower blowdown of Zhangjiakou power plant, Hebei province, and organic water treatment chemicals are added to the circulating cooling water for water treatment, so the cooling tower blowdown has the high viscosity. The three types of raw water mentioned above are named as Sample 1, Sample 2 and Sample 3, respectively. And the quality characteristic of three types of raw water samples are shown in Table 1.

2.2. Design of UF membrane system and selection of coagulant

Fig. 1 shows the schematic of the pilot test of UF system, which consists of coagulation process and UF

Table 1
Quality characteristic of 3 types of raw water used in the pilot test.

Items	Sample 1	Sample 2	Sample 3
pH	8.17	8.09	8.55
Temperature, °C	27.9	8.0	18.0
Turbidity, NTU	295.0	80.8	7.0
Conductivity, ms cm^{-1}	48.7	46.5	1.5
TDS, mg L^{-1}	36120	35560	1342
COD, mg L^{-1}	5.4	8.3	3.5
Content of total ferric, mg L^{-1}	2.50	1.60	0.20
Silica as SiO_2(colloidal), mg L^{-1}	9.0	14.0	140.0

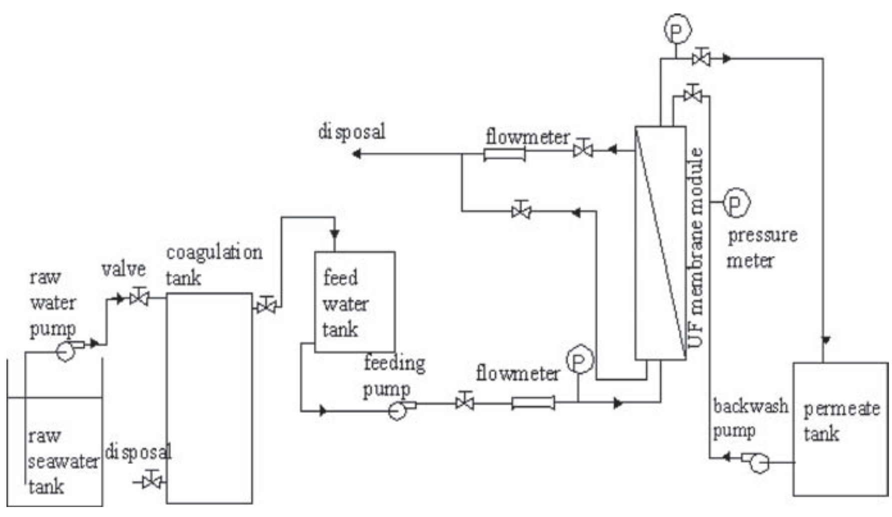

Fig. 1. Schematic diagram of the pilot scale test of UF system.

process. Coagulation process is used as the pretreatment process to meet the demand of feed water quality of UF process. In the coagulation process, the proper coagulant is selected due to the economical efficiency and the performance of coagulant.

In the pilot test, the coagulation tank, cartridge filter and the UF membrane (SXL-225 FSFC) module with the control system and data collection system is provided by the Harbin Duoxiang Company, the Beijing Jieming Company and the Netherland Norit Company, respectively.

The performance of UF membrane modules are evaluated by measuring the transmembrane pressure (TMP) in the constant flux operation mode. TMP for different fluxes is measured online using a transducer and the water temperature, flux and pH value are also tested continuously online. And the data measured online are recorded on a laptop computer via a data acquisition system.

The characteristics of UF membrane module used in this pilot test are shown in Table 2.

The three types of raw water named as Sample 1, Sample 2 and Sample 3 are far different from the water quality characterizations, so the operating parameters of UF membrane module in Sample 1, Sample 2 after coagulation process and Sample 3 without coagulation process are different. The operation parameters of UF system are shown in Table 3.

Table 2
Characterizations of UF membrane used in the pilot test.

Items	Characterizations
Membrane material	PES
Style	Inside-out hollow fiber
Membrane area, m^2	40
Nominal Pore Diameter, μm	0.03
Number of hollow fiber per Module	10992
Fiber inner/outer diameter, mm	0.8/1.5
Pure Water Permeability, L m^{-2} bar^{-1} h^{-1}	500

2.3. Chemical analysis

During the pilot test, the separation efficiency in the UF process is evaluated by measuring the reduction of COD, total dissolved ferric, colloidal silicon, turbidity, suspended solids (SS). The turbidity of effluent of UF process is measured by 2100 P Turbidmeter HACH, SDI_{15} is tested with the Millipore SDI membrane in the standard method to determine the quality characterization of UF permeate. The content of total organic carbon (TOC) is tested with Multi N/C 2100 TOC analyzer (Analytik Jena, Germany). The pH value and temperature are measured by using Orion PCM500 pH analyzer (Orion USA). The measurements of SS, the content of total dissolved ferric, silica and COD analysis are completed by following National standard methods of P. R. China, and the corresponding series number of test method is GB/T 11901-89, GB/T 14427-1993, GB/T 12150-1989 and SS-18-2-84, respectively.

3. Results and discussion

3.1. Experimental results of coagulation process

3.1.1. Selection of the proper coagulant

The coagulation process used as UF pretreatment system is very important for the separation efficiency of UF process, and the coagulant has an important performance on the coagulation process. During the coagulation experiment, four types of coagulants including polymer ferric sulfate (PFS), ferric chloride ($FeCl_3$), polymeric aluminum ferric sulfate (PAFS) and polymeric aluminum sulfate (PAS) are injected to the raw seawater of Sample 1 whose turbidity is 306 NTU, to remove

Table 3
Parameters of UF membrane module fed with different raw water in the pilot test.

Operation parameters	Sample 1	Sample 2	Sample 3
Water flux, L m^{-2} h^{-1}	70–95	60–110	60–110
pH value	7.80	7.58	8.60
Temperature, °C	27.8	8.0	18.0
Backwash (BW) duration, s	50–60	50	90
BW interval, min	20–30	30–45	20–30
BW water flux, L m^{-2} h^{-1}	250	225–250	194–240
Operating TMP, bar	0.16–0.26	0.14–0.25	0.5–1.1
Chemical enhanced backwash (CEB) Frequency, h	12–18	12–24	6–9
Cleaning chemical	HCl/NaClO	HCl/NaClO	HCl
Water recovery rate, %	78.5–92.4	90.9–94.3	66.5–81.8

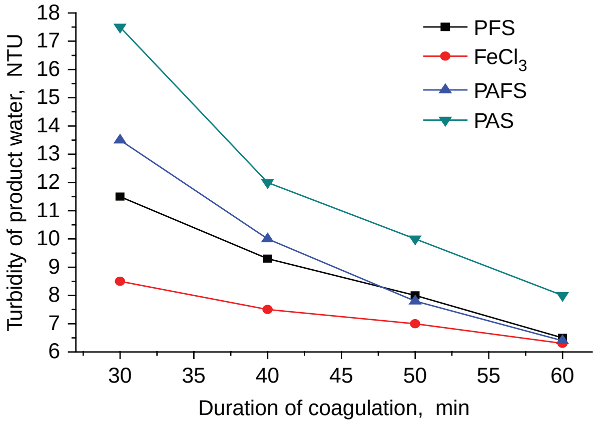

Fig. 2. Clarification effect of raw seawater treated with four types of coagulants.

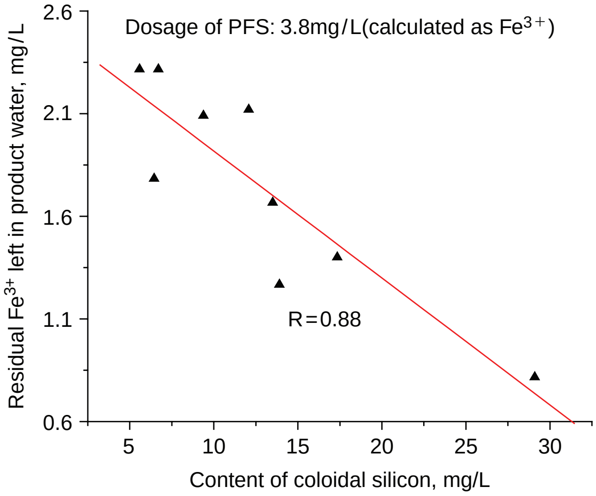

Fig. 3. Relationship between residual ferric in product water and the colloidal silicon in raw seawater.

turbidity of seawater and evaluate their performance on the coagulation process. The dosage of coagulants is 3.8 mg/L. The experimental results of coagulation process are shown in Fig. 2.

Fig. 2 indicates that ferric chloride has the best performance on the coagulation process. After the duration of 30 min., the turbidity of product water is 8.5 NTU after the coagulation process with the coagulant of ferric chloride, 11.5 NTU with PFS, 13.5 NTU with PAFS, and 17.5 NTU with PAS. However, taking the consideration of economical efficiency and coagulation performance, PFS of low price is selected as the coagulant instead of ferric chloride in the pilot test.

3.1.2. Effluent quality of coagulation process

In the coagulation process of the pilot test, raw seawater of Sample 1 and Sample 2 are used and they are far different in turbidity and temperature, but the same dosages of PFS are added into the water samples. Fig. 3 indicates the relationship between the residual ferric remained in product water and the concentration of colloidal silicon in raw seawater with the addition of 3.8 mg/L PFS as Fe^{3+}.

Fig. 3 reveals that when the dosage of PFS is fixed, there is linear relationship between residual ferric in product water and the content of colloidal silicon remained in raw seawater. So the optimal dosage of PFS can be determined by measuring the concentration of colloidal silicon.

During the coagulation process, 3.8 mg/L PFS calculated as Fe^{3+} is added to the raw seawater of Sample 1 and Sample 2, the quality characterizations of the effluents of Sample 1 and Sample 2 after coagulation process are shown in Table 4.

Table 4 illustrates that after the coagulation process, the turbidity, contents of suspended solids, TOC, COD, and silica as SiO_2 are reduced, it means that the coagulation process can remove parts of TOC, COD, silica and improve the clarity of raw water. However, in the raw water of Sample 2, the content of ferric increases, and the reason is that the hydrolyzing process of the coagulant is greatly influenced by low water temperature and the coagulant has no good performance on the coagulation process because of low temperature.

3.2. Optimization of operating parameters of UF membrane

Fig. 4 shows that the relationship between the permeation flux and TMP of UF membrane when Sample 1 and Sample 2 after coagulation process and Sample 3 without coagulation process are passed through the UF membrane. As demonstrated in Fig. 4, initially, the relationship between permeation flux and TMP is obviously linear, and as the permeation flux increases, the relationship between permeation flux and TMP develops the nonlinear rule. It was well known that the flux variationin permeate of membrane filtration induced by pore blocking could be usually divided into three stages [3]. For the first stage, pore is partially blocked with particles and the effective filtration area decreases. After that, the cake layer is formed on the surface of membrane and the permeate flux decreases gradually. Finally, the permeate flux tend to be steady. The above pore blocking mechanisms could be well described with Hermia model which is expressed in Eq. 1 [4]:

$$\frac{dJ}{dt} = -k \cdot J \cdot (J \cdot A_0)^{n-2}, \tag{1}$$

where t denotes the filtration time, J denotes the permeation flux of membrane process and A_0 denotes the

Table 4
Quality characterizations of effluents after coagulation process in the pilot test.

Parameters	Sample 1 after coagulation	Sample 2 after coagulation
pH	7.80	7.58
Temperature, °C	27.9	8.0
Turbidity, NTU	10.2	9.4
Suspended solid, mg L^{-1}	5.0	2.6
TOC, mg L^{-1}	1.10	5.90
COD, mg L^{-1}	3.5	7.33
Content of total ferric, mg L^{-1}	0.63	2.03
Silica as SiO_2, mg L^{-1}	2.6	2.16

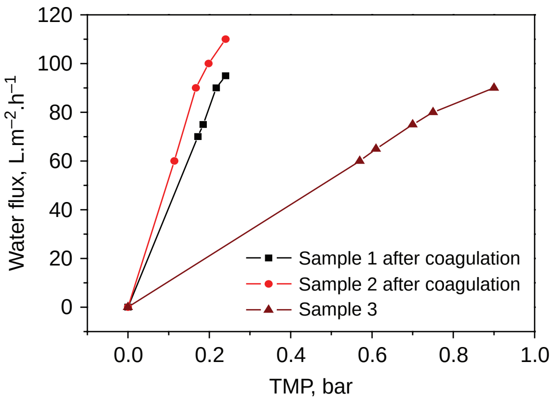

Fig. 4. Relationship between permeation flux and TMP of UF membrane fed with three different types of raw water.

effective filtration area of UF membrane. The parameter n characterizes the filtration model, with n = 0 for cake filtration, n = 1 for intermediate blocking, n = 3/2 for pore constriction (standard blocking), and n = 2 for complete pore blocking. The UF membrane resistance can be described with the Tracey equation which is expressed in Eq. 2 [5]:

$$R_{\text{total}} = \frac{\Delta P}{\mu \cdot J}. \quad (2)$$

Eq. 2 also can be transformed into Eq. 3:

$$\frac{1}{R_{\text{total}}} = \frac{\mu \cdot J}{\Delta P}, \quad (3)$$

where μ denotes the viscosity of the solution and ΔP denotes the transmembrane pressure. Tracey and Davis shows that a plot of $\frac{1}{R_{\text{total}}}$ as a function of time is concave down when n > 1 and is concave up when n £ 1. And it illustrates that once the increment of flux ($^{\mathrm{d}J}/_{\mathrm{d}t}$) lowers, the membrane fouling model changes, and the critical flux (theoretically optimal flux) would appear. So the better method of fixing critical flux is that once the increment of water flux decreases as the increment of TMP increases, the critical flux of UF membrane would appears, it means that if the line of water flux and TMP has the turning point, the critical flux can be fixed.

And there is another method to get the optimal flux by TMP-constant operating mode experiment. Increasing TMP step by step till the permeate flux of UF membrane would not increase any longer and tend to be steady, and the steady flux of UF membrane that is the limiting flux appears, and the critical flux is equal to two third of the limiting flux [6].

During the UF process, it is important to optimize the backwash interval and other backwash parameters, because the optimal backwash parameters maximizes the average product water flux and improve the recovery rate.

3.3. Filtrate quality of UF process

Table 4 shows the water quality characterizations of the permeate of UF system in the pilot test when fed with three different types of raw water samples including Sample 1 after coagulation process, Sample 2 after coagulation process, and Sample 3 without coagulation process. Due to difference in the quality characterizations of Sample 1 after coagulation process, Sample 2 after coagulation process and Sample 3 without coagulation process which are used as the feed water of UF process, the permeates of UF process are different from the pH value, the content of COD and silica. However, the turbidity, content of total ferric, silica and SDI_{15} are similar, and the other quality characterizations of permeates of UF membrane are similar. So it indicates that the UF membrane module can offer the permeate of stable quality characterizations, which can meet the feeding requirement of reverse osmosis (RO).

3.4. Comparison of flux, TMP and permeability in three types of water samples

The UF process operates in the steady-flux mode, and optimizes the flux due to membrane fouling performance when the UF membrane is fed with three types of raw water samples. The variation of flux and TMP of UF membrane in Sample 1, Sample 2 after coagulation process and Sample 3 without coagulation process are shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

Fig. 5, Fig. 6 and Fig. 7 reveal that the UF membrane has the similar performances on Sample 1 and Sample 2

Table 5
Effluent quality of the UF membrane.

Items	Sample 1 after UF process	Sample 2 after UF process	Sample 3 after UF process
pH	7.82–8.01	7.57–7.71	8.2–8.75
COD, mg/L	0.55–4.56	5.03–7.29	1.7–2.9
Content of total ferric, μg L^{-1}	11.9–34.5	8.33–13.33	9.6–49.2
Silica as SiO_2, mg L^{-1}	0.41–1.97	0.10–0.11	0.80–1.20
Turbidity, NTU	0.06–0.11	0.07–0.10	0.28–0.31
SDI_{15}	1.00–2.58	2.18–2.57	1.09–2.34

after coagulation process although the effluents of Sample 1 and Sample 2 after coagulation process are far different from the temperature, while the performance on Sample 3 without coagulation process is greatly different from the performances on Sample 1 and Sample 2 after coagulation process. They indicate that the key influence factor on the performance of UF membrane is not the temperature of feed water but the components of feed water, especially the content of silica and other colloids which lead to the membrane fouling.

Fig. 8 shows the tendency of permeability of the UF membrane in the pilot test, the UF membrane has the higher permeability when UF membrane is fed with Sample 1 and Sample 2 after coagulation process, while the lower permeability when UF membrane is fed with Sample 3 without coagulation process.

Membrane fouling performs as the permeability of UF membrane drops, expressed as normalized flux divided by TMP. It is reported that coagulation process could help increase membrane flux and prevent membrane from fouling [7]. And a relatively rapid irreversible

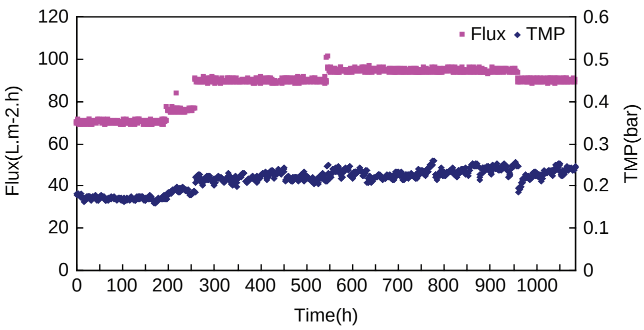

Fig. 5. Variation of flux and TMP of UF membrane on Sample 1 after coagulation.

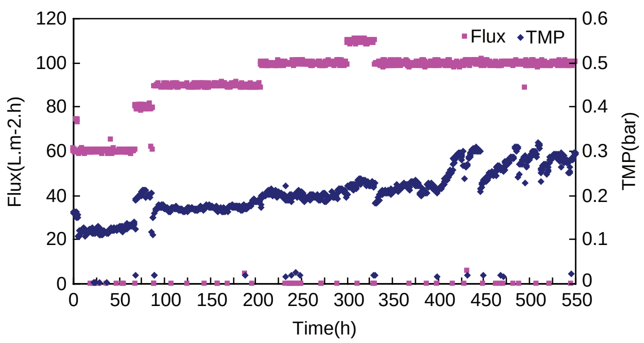

Fig. 6. Variation of flux and TMP of UF membrane on Sample 2 after coagulation.

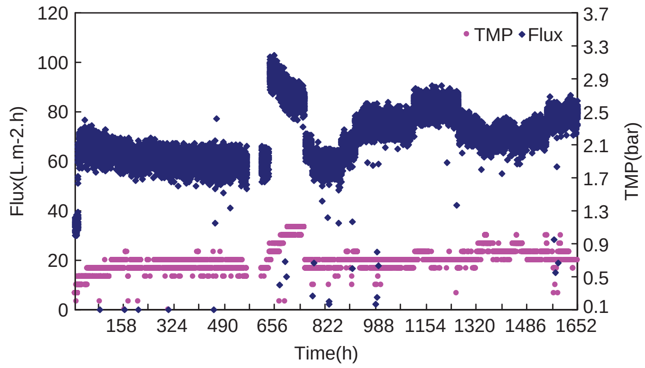

Fig. 7. Variation of flux and TMP of UF membrane on Sample 3 without coagulation.

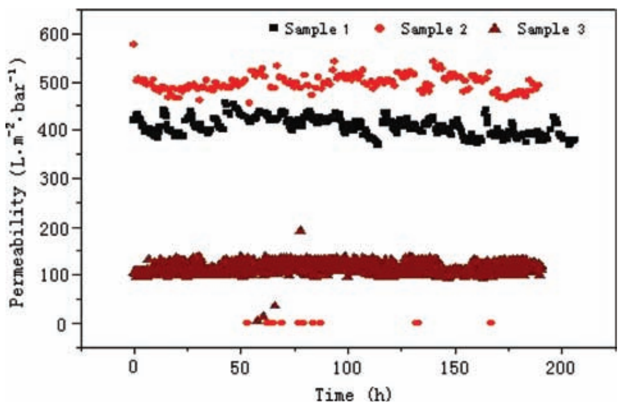

Fig. 8. Tendency of permeability of the UF membrane in the tests.

fouling of the membrane took place due to adsorption within the membrane pores [8]. So at the absence of coagulation process, organic water treatment chemicals leading to high viscosity of the cooling tower blowdown can cause of lower permeability in the pilot test.

4. Conclusions

During the pilot test, the key influence factor of the membrane fouling is not the temperature but the components of feed water, especially the content of silica and other colloids. So reducing silica and other colloids by coagulation process can prevent the UF membrane from fouling. During the coagulation process, ferric chloride has the best performance on the coagulation process, but taking the consideration of economical efficiency and coagulation performance, PFS is the appropriate coagulant for seawater coagulation, and the dosage of PFS is mainly influenced by the concentration of colloidal silicon dissolved in the seawater.

During the UF process, the UF membrane module (SXL-225 FSFC) can offer the permeate of stable quality characterizations, which can meet the feeding requirement of reverse osmosis (RO). And it is an effective method to optimize the membrane flux in pilot test by the application of graph of membrane flux versus TMP.

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