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Novel ultrafiltration membrane fouling control method with *in-situ* filter aid of perlite particles

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ABSTRACT

Perlite particles were used as filter aid and added directly into the feed solution. A loose filter aid layer was formed on the membrane surface during ultrafiltration (UF) process. The layer could prevent contaminant from adhering onto membrane surface directly. The filter aid layer could be easily removed from membrane surface by oscillation of the membrane module and the membrane could be regenerated as a result. The effects of the size and dosage of perlite particles and UF operating conditions (including the transmembrane pressure and feed velocity) on the performance of the process were studied. The results showed that the addition of perlite particles could reduce the filtration resistance and the particles with the size of 100–150 μm could cause more resistance reduction than the smaller ones. When operated at 0.075 MPa with a feed velocity of 0.055 m/s, the filter aid efficiency and flux increase were balanced. The J/J_0 increased 7% and the flux recovery rate enhanced 25% compared with UF process without perlite.

Keywords: Ultrafiltration; Membrane fouling; Filter aid assisted membrane process; Filtration resistance analysis

1. Introduction

With the development of membrane technology, the low-pressure membrane processes, such as microfiltration (MF) and ultrafiltration (UF), have been increasingly used in potable water treatment [1–4] as well as in advanced treatment of effluents from wastewater processing plants [5] in the past decades. UF is employed to remove microparticles and macromolecules, which generally include inorganic particles, organic colloidal, and dissolved organic matters [6]. However, fouling which arose from specific interactions between the membrane and the contaminants in the feed is still a persistent problem restricting the development of UF. Theoretically, fouling of UF membranes can be divided into three types: Pore constriction due to adsorption of contaminants into the pores, pore blocking, and cake layer formation [7]. Fouling of the membrane causes deterioration of membrane materials as well as decreases membrane performance (in terms of flux). So fouling is one of the critical issues in the successful application of membrane systems for water treatment.

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Many methods are applied to control membrane fouling. Among them, the pretreatment of the feed is one of the most popular and effective methods. The pretreatment, such as coagulation, adsorption, and ozonation, before the membrane technology, has been used to remove natural organic matter and to mitigate fouling [8]. Membrane fouling can also be alleviated by some special designs in membrane geometry and module structure, by adjustment of membrane surface flow velocity and turbulent pulse, and by electric or electromagnetic influence [9–13]. In addition, dynamic membrane (DM) technology is also an effective method to inhibit membrane fouling. DM is formed on an underlying membrane when the feed solution contains suspended solid particles such as microbial cells and flocs. In fact, DM was a cake layer which can prevent fouling adhering on the membrane surface. DM technology has been widely used in MF, UF, and membrane bioreactor [13–16].

Filter aid is a kind of auxiliary materials used to control flow and remove contaminants by forming a porous layer on the surface of the septum. The porous layer works as a filtering medium that traps the contaminants and prevents them from blinding the septum. Filter aid is rigid intricately shaped, porous individual particles, and can form a highly permeable, stable, and incompressible cake. Besides, filter aid is chemically inert and essentially insoluble in the liquid being filtered and widely used in many fields such as beverage industry, beer industry, paper industry, and wastewater treatment [17]. Commonly used filter aid includes diatomite, perlite, cellulose, and asbestos. There are two main methods to add filter aid. One is mixing filter aid with liquid by a certain proportion to form a suspension; and the other is forming a precoating layer of filter aid on the filter media [18].

Perlite is an amorphous volcanic glass characterized by relatively high water content, typically formed by the hydration of obsidian [19]. It is an excellent filter aid and used extensively as an alternative to diatomaceous earth. Commercial applications of perlite are due to its low density and low price. In the construction and manufacturing fields, it is used in lightweight plasters and mortars, insulation and ceiling tiles. In the filtration process, the perlite powders are bonded to each other to form a porous layer on the filter cloth or filter paper that can achieve rapid filtration owing to the large numbers of tiny and connective pores [20]. So far there are few research reports about using filter aid in a membrane process. More researches focused on using filter aid in filtration pretreatment [21,22].

In this work, *in situ* filter aid assisted UF process was constructed. Perlite filter aid was combined with membrane separation process by mixing directly in the feed solution. A loose cake layer was formed on membrane surface during UF process, which could prevent membrane fouling from contaminants adhering on membrane surface directly. The loose cake layer could be easily removed from membrane surface by intermittent oscillation cleaning, thus the membrane was regenerated, as showed in Fig. 1. The effects of the size and dosage of the perlite filter aid particles and operating conditions on the performance of UF process were studied. UF resistance model based on Darcy's Law was adopted in membrane fouling analysis, and scanning electronic microscope (SEM) was used in membrane surface morphology and fouling characterization. Through this work, we

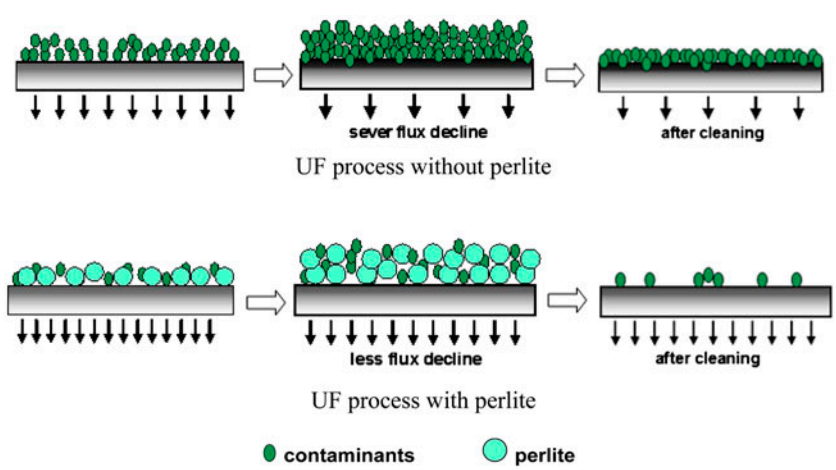

Fig. 1. Theoretical conception of *in situ* filter aid UF process.

expect to obtain an *in situ* filter aid assisted UF process, which can balance the initial flux enhancement, the reduction of filtration resistance and the filter aid efficiency (partially characterized by flux recovery rate).

2. Materials and methods

2.1. Materials

Polyvinylidene fluoride (PVDF) hollow fiber UF membrane and cylinder module was used in the following experiments. Structural parameters of the membrane and module were listed in Table 1.

The secondary sedimentation tank effluent from Tianjin Dongjiao wastewater treatment plant was used as the feed water in this research. The turbidity value of the feed water was 3.96–1.71 NTU, and the value of the chemical oxygen demand (COD_{cr}) was about 45 mg/L.

Two specifications of perlite with different particle sizes (25–50 and 100–150 μm) were supplied by Xinyang Perlite Factory.

2.2. UF test equipment and operation method

The flowchart of UF process was shown in Fig. 2. The perlite filter aid was directly added in the feed water. The feed water flowed into the shell side of the membrane module and the product water was pumped from the lumen side. The membrane was operated in cross-flow mode at constant pressure. The feed water was replenished continuously in order to maintain its volume constant (4.0 L) during the experiment. The weight of product water was measured every 10 min and the membrane flux was calculated by Eq. (1) [17]:

$$J = \frac{W}{S \times t} \tag{1}$$

Table 1
Structural parameters of PVDF hollow fiber membrane and module

Membrane			Module		
ID[a]/mm	OD[b]/mm	Pore size/μm	Packing density/%	Length/mm	Area/m^2
0.6	1.0	0.10	9.0	240	0.075

[a]Inside diameter of the membrane.
[b]Outside diameter of the membrane.

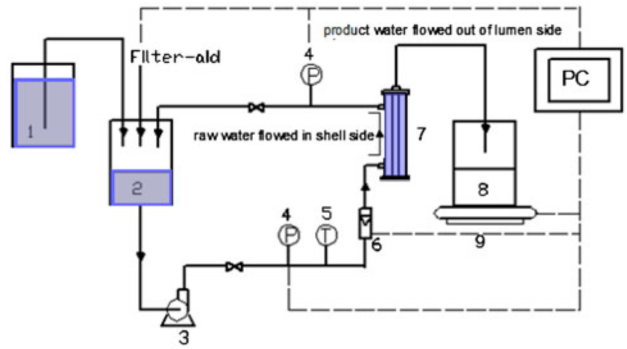

Fig. 2. *In-situ* filter aid UF experimental apparatus.
1. raw water tank; 2. reservoir; 3. pump; 4. pressure gage; 5. thermometer; 6. flowmeter; 7. membrane module; 8. clean water tank; 9. electronic balance.

where J is the membrane flux, kg/(m^2h); W is the weight of the product water, kg; S is the effective membrane area of hollow fiber membranes, m^2; and t is the time of the product water collection in the UF process.

Normalized flux, E, was adopted to characterize the flux reduction during the UF process,

$$E = J/J_0 \tag{2}$$

where J and J_0 are the membrane flux tested at time t and the beginning of the experiment, respectively.

The membrane module was oscillation cleaned every 40 min (one cycle) and furthermore, the filter aid adhered on the surface of the membrane was recovered by filtering the concentrated water with a sieve.

Flux recovery rate (E_R) was defined as

$$E_R = E_c - E_e \tag{3}$$

where E_c and E_e are J/J_0 with and without oscillation cleaning at the end of each cycle, respectively.

Flux decline rate (E_D) was defined as

$$E_D = E_b - E_e \tag{4}$$

where E_b denotes the J/J_0 at the beginning of the cycle (from the second cycle beginning, E_b is E_c, which mentioned in Eq. (3)).

2.3. Analytical methods

The turbidity was measured by a turbidity meter (HACH-2100P). COD was measured by the chrome method with the microwave dissolver (Qingdao Kedi

Bo Electronic Science and Technology Co., Ltd). Morphological analysis of the membranes was performed by a scanning electronic microscope (SEM, JSM-6460LV, Japan). After each experiment, the membrane samples were dried in vacuum drying oven, then the samples were fractured in liquid nitrogen and then coated with gold for electron conductivity before they were observed by SEM [23].

2.4. Resistance model

Flux decline is a result of the increase in membrane resistance to the permeating flow, caused by membrane fouling or particle deposition on or in the membrane. Analysis of the resistance is an effective approach to illustrate the filter aid assisted UF process.

The resistance models are based on Darcy's Law. The permeate flux decreases as a function of the resistances caused by the fouling phenomena. The permeate flux, J may be expressed by Eq. (5) [24]:

$$J = \frac{\Delta P}{\mu R} \tag{5}$$

where ΔP is the transmembrane pressure (TMP), R is the total resistance, and μ is the viscosity of the feed water which was determined by Ubbelohde viscometer.

In this study, the resistance is considered to be consisting of three parts, that is, $R = R_m + R_c + R_o$, so Eq. (5) is rewritten as:

$$J = \frac{\Delta P}{\mu(R_m + R_c + R_o)} \tag{6}$$

where R_m is the resistance of the membrane, R_c is the resistance due to the cake layer, and R_o is the resistance caused by contaminants.

The R_m (intrinsic resistance of a membrane) can be evaluated directly from the slope of the pure water flux (J_w) vs. pressure data, as showed in Eq. (7):

$$R_m = \frac{\Delta P}{J_w} \tag{7}$$

This study used the permeate flux that was obtained after 40 min of sustained UF for the calculation of the total resistance, R, by Eq. (5). Afterward, the membrane was rinsed with distilled water thoroughly after oscillating cleaning in order to wash off the depositions on membrane surface. With this rinsed membrane, the pure water run was conducted at the same operating conditions. By doing this, the R_f (reversible fouling resistance) was eliminated by Eq. (8). The R_c could be calculated by Eq. (9):

$$J = \frac{\Delta P}{\mu R_f} \tag{8}$$

$$R_c = R - R_f \tag{9}$$

Then, the R_o was eliminated by Eq. (6).

3. Results and discussion

3.1. Effect of perlite particle size on filter aid assisted UF process

Two types of perlites with different particle sizes (25–50 and 100–150 μm) were added into the feed solution of UF process, separately. The dosage of perlite was 4.0 g, relative to 53.3 g for each 1.0 m^2 membrane filtration area. The UF experiment was carried out at 25℃, 0.040 MPa TMP with the feed flow rate of 0.055 m/s.

The initial fluxes of the UF experiments with perlite addition in the feed were 119.7 kg/m^2 h (25–50 μm) and 119.1 kg/m^2 h (100–150 μm), while it was only 113.7 kg/m^2 h without perlite addition.

J/J_0 was applied to characterize the flux declination and reclamation trend of the UF experiments, the results were shown in Fig. 3.

It can be seen that the J/J_0 declined with UF operating time in the three cycles and recovered to some

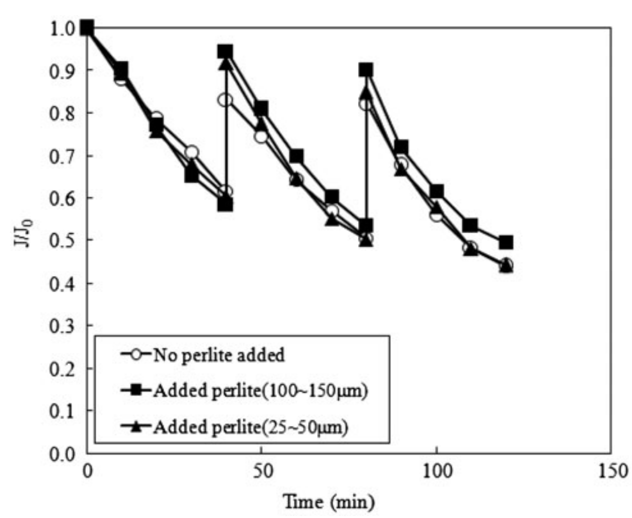

Fig. 3. Effect of perlite particle size on the normalized flux during the UF process.

extent after each oscillation cleaning step. As far as the first cycle concerned, there had no significant difference in the trend of flux decline. The E_e of three processes were very close and near 0.6. However, the difference was clearly observed after oscillation cleaning. In the case of UF process without perlite, the E_c in the next two cycles were 0.83 and 0.82, respectively, whereas the UF with perlites addition was 0.92, 0.85 (25–50 μm) and 0.95, 0.90 (100–150 μm).

The results indicated that the addition of perlites as filtration aids in UF process could slowly enhance the initial flux, alleviate J_D and increase E_R, to some extent. When perlite (100–150 μm) was used, the J_D was lower and E_R was higher than the J_D and E_R when perlite (25–50 μm) was used.

What's more, to estimate the resistance caused by perlite in the filtration process, UF filtration experiment was carried out using pure water with perlite added as the feed solution. The operation conditions of the process were the same as those using the wastewater as the feed.

Two mechanisms, the adsorption of contaminants on the perlite and the filtration aid effect (bridge effect of perlite on membrane surface), maybe the way that perlite works in the procedure. To analyze the key mechanism of them, the perlite was pre-immersed in the feed wastewater for 20 d to make sure that adsorption saturation was reached. Then the perlite was adopted as the filter aid and UF experiments were carried out at the same conditions.

Membrane filtration resistance model was adopted to analyze these filtration results. The resistances of each part of the membrane fouling during these UF processes were calculated according to the method introduced before. The results were listed in Table 2.

The results in Table 2 showed that, in the case of UF process without perlite, all of the resistances (R, R_o and R_c) were the highest. When perlite was added, three kinds of resistances were considerably reduced compared to that of UF process without perlite. In addition, in the case of perlite (100–150 μm) adopted, the highest resistances decrease can be observed.

The results indicated that perlite filter aid addition can effectively alleviate membrane fouling. The reduction of cake resistance and organic fouling resistance was attributed to the looser cake layer containing perlite, which prevent colloids and other contaminants from attaching to the surface of membrane directly so as to cause the initial flux increase. Moreover, the looser cake layer containing perlite was fairly easy to remove by oscillation cleaning.

Furthermore, the cake layer formed in the UF process adopted perlite with particle size of 100–150 μm might be more porous and looser than that formed in the process used perlite (25–50 μm), owing to the bigger particle size. As a result, the UF process adopted perlite (100–150 μm) had higher flux and better antifouling property. Therefore, perlite with particle size of 100–150 μm was used in the following work.

What's more, when pure water with perlite was used as the feed, the total resistance, R, is mainly due to the membrane resistance, R_m. While the resistance of cake layer, R_c, which may be caused by pure perlite deposition on membrane surface, is only 6% of R_m. This partially testified that the addition of perlite as filter aid would not obviously increase filtration resistance.

As for the experiment that wastewater with pre-immersed perlites was used as the feed, the resistances, R, R_m, and R_0 are quite similar to those using unimmersed perlites. This testified that the bridge effect is dominant offered by filter aid. The adsorption of contaminant on the filter aid agent, perlite, is negligible.

Fig. 4 illustrated the surface SEM pictures of the membranes used in UF processes with and without perlites.

For the process without perlite addition, the membrane surface was covered with obvious deposition, as shown in Fig. 4(a). When the membrane was cleaned by oscillation method, there was still contaminant remained on the membrane surface (Fig. 4(b)). As for that using perlite as filter aid agent, the membrane surface was covered with much more deposition (Fig. 4(c)), which may be composed of perlite and

Table 2
Effect of perlite addition on the filtration resistances of UF process

Process	UF (no perlite)	UF + perlite (25–50 μm)	UF + perlite (100–150 μm)	UF (pure water) + perlite (100–150 μm)	UF + perlite (100–150 μm, pre-immersed)
R/R_m	2.54	2.38	2.16	1.10	2.16
R_c/R_m	1.33	1.20	1.06	0.06	1.07
R_o/R_m	0.21	0.17	0.10	0.00	0.09

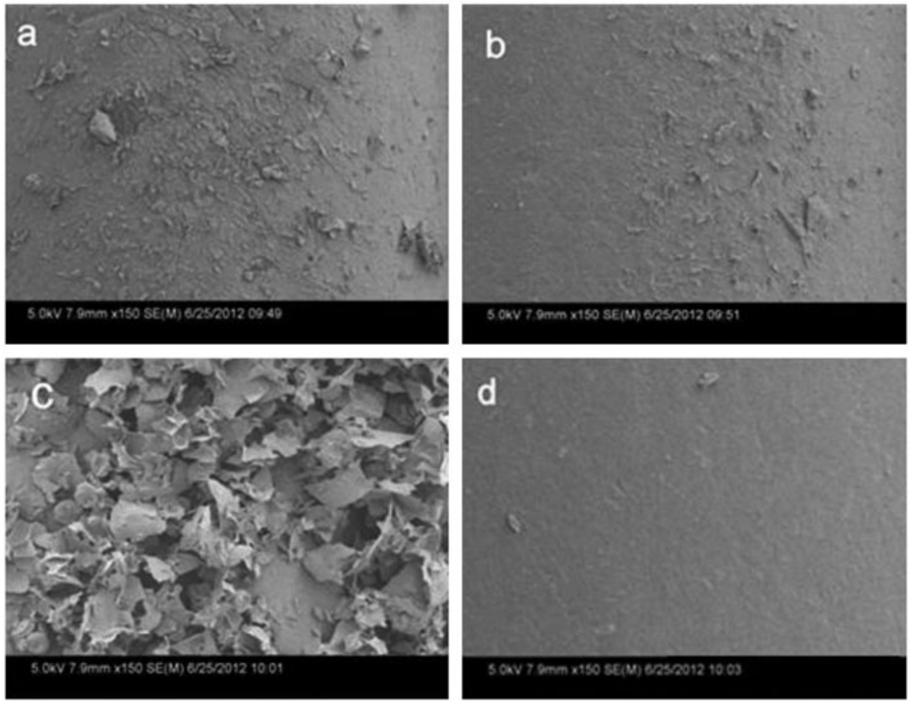

Fig. 4. Surface images of the membranes used in the UF process with or without perlite. (a) Membrane used in UF process without perlite added, (b) the membrane (a) after oscillation cheaning, (c) membrane used in UF process with perlite, (d) the membrane (c) after oscillation cleaning.

contaminants. However, after oscillation cleaning, there's only little deposition left on membrane surface. These illustrated that the addition of filter aid, perlite, could help to reduce membrane surface fouling during UF process.

3.2. Effect of perlite dosage on filter aid assisted UF process

Wastewater with 4.0, 8.0, and 12.0 g perlite addition was adopted as the feed of UF process separately to study the effects of perlite dosage on the UF performance and membrane fouling. The UF experiments were carried out at 25℃ and 0.040 MPa with the feed flow rate of 0.055 m/s.

Compared with the UF process without perlite, the initial fluxes of the UF process with perlite were enhanced by 13% (4.0 g), 16% (8.0 g) and 17% (12.0 g), respectively. J/J_0 was applied to characterize the flux decline and reclamation trend of the UF experiments, the results were shown in Fig. 5.

It can be seen that the J/J_0 declined with time in the three cycles and recovered to some extent after each oscillation cleaning step. In the first cycle, the decline trend of four processes was similar but the E_e was different, which was 0.48 (without perlite), 0.45 (4.0 g perlite), 0.53 (8.0 g perlite), and 0.45 (12.0 g perlite), respectively.

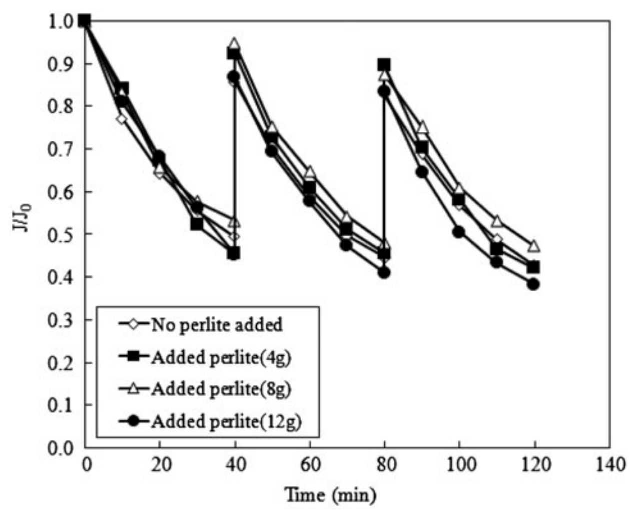

Fig. 5. Effect of perlite dosage on the normalized flux, J/J_0, during the UF process.

As far as the second cycle concerned, the E_b (E_c) was 0.92 (4.0 g perlite), 0.95 (8.0 g perlite), and 0.87 (12.0 g perlite), separately. While that using the feed solution without perlite was 0.86.

At the end of the third cycle, the E_e of UF process without perlite was 0.43, while that of UF added 8.0 g perlite was 0.47.

The figure indicated that the higher dosage of the filter aid, perlite, was not necessarily better. In the case of 8.0 g perlite adopted, the flux decline was the least and more reversible compared to the rest dosages.

Membrane filtration resistance model was adopted to detect the reason of the results. The filtration resistances of these UF processes were calculated according to the method introduced before, and the results were listed in Table 3.

The results in Table 3 showed that, in the case of UF process without perlite, all of the resistances (R, R_o, and R_c) were the highest. When perlite was added, three kinds of resistances were considerably reduced. In the case of 8.0 g perlite added, relative to 106 g for each 1.0 m^2 membrane filtration area, all of the resistances decreased most.

The results revealed that the dosage of the perlite has a close relation with the filter aid assisted UF process. The dosage of 4.0 g was far from adequate to sufficiently change the porosity of the deposited cake to achieve the best filtering effect. When the dosage of perlite was excessive, too thick cake layer might be formed which might cause the increase of the R_c, as reported in Table 3. Therefore, filter aid agent adopted in the process required a suitable dosage and 8.0 g was the optimum one for this experiment. Therefore, wastewater with 8.0 g perlite addition was adopted as the feed of the UF process in following work.

3.3. *Effect of TMP on filter aid assisted UF process*

The UF experiment was carried out at 25˚C and a feed flow rate of 0.055 m/s, while the TMP was adjusted to 0.020, 0.040, 0.075, and 0.099 MPa. Fig. 6 illustrated the permeate flux J and J/J_0 at different TMP, respectively. The variation of flux in each stage of three cycles was also listed in Table 4.

According to Darcy's law, pressure is the driving force for mass transfer through the membrane [25]. The average permeate flux is, therefore, expected to be higher with an increased TMP. However, when TMP exceeded a critical value, the increasing rate of permeate flux with TMP would decrease due to the aggravation of concentration polarization and membrane fouling [26].

Table 3
Effect of perlite dosage on the filtration resistances of UF process

Process	UF (no perlite added)	UF + 4.0 g perlite	UF + 8.0 g perlite	UF + 12.0 g perlite
R/R_m	1.99	1.69	1.63	1.75
R_c/R_m	0.81	0.63	0.61	0.73
R_o/R_m	0.18	0.06	0.02	0.02

From Fig. 6, it could be seen that as for the UF process without perlite addition, the initial flux was apparently enhanced from 65.4 to 318.5 kg/m^2 h as the TMP increased from 0.02 to 0.099 MPa. In the second cycle, the E_R was enhanced from 30 to 55% and the E_D was enhanced from 30 to 58% as the TMP increased from 0.02 to 0.099 MPa.

As for the UF process with perlite addition, the variation of permeate flux showed the same trend compared with reference [26]. The permeate flux

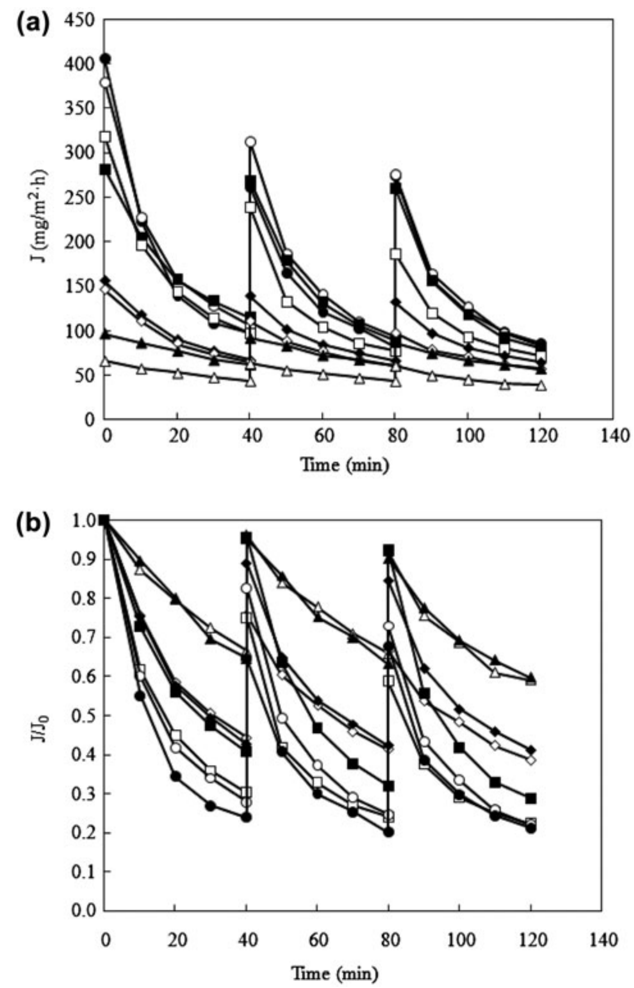

Fig. 6. Effect of TMP on the permeate flux and normalized flux during the UF process.

Table 4
The variation of flux in the three cycles of UF with different TMPs

			E_b	E_R	E_e	E_D (%)
The first cycle	0.020 MPa	UF	1.00	—	0.66	34
		UF + 8.0 g perlite	1.00	—	0.65	35
	0.040 MPa	UF	1.00	—	0.44	56
		UF + 8.0 g perlite	1.00	—	0.43	57
	0.075 MPa	UF	1.00	—	0.31	69
		UF + 8.0 g perlite	1.00	—	0.41	59
	0.099 MPa	UF	1.00	—	0.28	72
		UF + 8.0 g perlite	1.00	—	0.24	76
The second cycle	0.020 MPa	UF	0.96	30%	0.66	30
		UF + 8.0 g perlite	0.95	30%	0.63	32
	0.040 MPa	UF	0.76	32%	0.41	35
		UF + 8.0 g perlite	0.89	46%	0.42	47
	0.075 MPa	UF	0.75	45%	0.24	51
		UF + 8.0 g perlite	0.96	55%	0.32	64
	0.099 MPa	UF	0.83	55%	0.25	58
		UF + 8.0 g perlite	0.64	40%	0.20	44
The third cycle	0.020 MPa	UF	0.92	26%	0.59	33
		UF + 8.0 g perlite	0.90	27%	0.59	31
	0.040 MPa	UF	0.66	25%	0.38	28
		UF + 8.0 g perlite	0.85	43%	0.41	44
	0.075 MPa	UF	0.59	35%	0.22	37
		UF + 8.0 g perlite	0.92	60%	0.29	63
	0.099 MPa	UF	0.73	48%	0.22	51
		UF + 8.0 g perlite	0.68	48%	0.21	47

increasing rate kept constant first and then decreased as the TMP increased from 0.02 to 0.099 MPa. Furthermore, the addition of perlite showed obvious effect on the E_R and J/J_0, and the effect of perlite addition related with the TMP. When the TMP was 0.075 MPa, the E_R enhanced by 10 and 25% separately in the second and third cycle compared to the UF process without perlite addition. As for the processes with other TMPs, the recovery of J/J_0 owing to the addition of perlite was lower than that with TMP of 0.075 MPa.

Membrane filtration resistance model was adopted to analyze the reason of the results. The filtration resistances during these UF processes were calculated according to the method introduced before, and the results were listed in Table 5.

The results in Table 5 showed that, in the case of 0.020 MPa TMP adopted, all of the resistances of the two processes (with and without perlite) were very similar. When the TMP was increased from 0.040 to 0.075 MPa, three kinds of resistances of filter aid UF process were considerably reduced compared to that of UF process without perlite. In addition, in the case of 0.075 MPa TMP adopted, all of the resistances had the most significant reduction. Nevertheless, when the TMP was increased up to 0.099 MPa, nearly all of the resistances were considerably increased compared to that of UF process without perlite.

As for the UF process without perlite, R, R_c, and R_o all increased with TMP. As for the UF process with perlite, R and R_c also increased with the TMP. The reason for this result was that the accumulation of contaminant was accelerated at higher TMP. While, as for the UF process with perlite, R_o increased first at 0.02–0.04 MPa, then decreased at 0.04–0.075 MPa, and increased again at 0.075–0.099 MPa. Combining with the analysis of permeate flux in Fig. 6, the variation of R_o for the process with perlite addition might be related to the operation mode. When TMP was low, it was difficult to form a complete filter aid cake layer. Thus, pollutants still adhered onto the membrane surface to increase the irreversible resistance (R_o). While when the TMP increased, the formed filter aid cake layer would be more complete and R_o would decrease. When the TMP reached 0.075 MPa, the filter aid cake layer could be quickly formed and the pressure could not destroy the "rigid bridge" structure of the perlite layer which could still keep at high porosity state. Therefore, the inhibitory effect on the membrane fouling was the most significant when the TMP was 0.075 MPa. However, when the TMP was enhanced up to 0.099 MPa, the "rigid bridge" structure of the

Table 5
Effect of TMP on the filtration resistances of the UF process

Resistance		R/R_m	R_c/R_m	R_o/R_m
0.020 MPa	UF	1.45	0.40	0.04
	UF + 8.0 g perlite	1.49	0.43	0.05
0.040 MPa	UF	2.31	0.96	0.34
	UF + 8.0 g perlite	2.16	0.95	0.20
0.075 MPa	UF	3.17	1.83	0.33
	UF + 8.0 g perlite	2.35	1.26	0.09
0.099 MPa	UF	3.44	2.08	0.36
	UF + 8.0 g perlite	4.00	2.79	0.21

perlite would be destroyed. In addition, the rejected solute together with the perlite particles might be compressed into a dense fouling layer, which would increase the UF resistance. So R_o increased again at 0.075–0.099 MPa and the total resistance at 0.099 TMP was the highest, as reported in Table 5. Therefore, 0.075 MPa is the optimum TMP for the filter aid assisted UF process.

3.4. Effect of feed flow rate on filter aid assisted UF process

The UF experiment was carried out at 25℃ and 0.075 MPa TMP, while the feed flow velocity was adjusted to 0.017, 0.055, and 0.076 m/s, the corresponding Reynolds numbers were 19, 61, and 85, respectively.

Compared to the UF process without perlite, the initial flux of the UF process with perlite enhanced by 1.4% (0.017 m/s), 3.4% (0.055 m/s), and 6.4% (0.076 m/s), separately. J/J_0 was applied to characterize the flux decline and recovery of the UF experiments, the results were shown in Fig. 7. The variation of flux in the three cycles was listed in Table 6.

It can be seen that in the first cycle, no significant difference in the trend of flux decline can be observed. The E_e of the cycle were very close and near 0.30. However, the difference was clearly observed after oscillation cleaning. For one thing, the flow rate of the feed solution showed great effect on the E_R and E_D. As for the UF process without perlite added, the E_b was enhanced from 0.54 to 0.87 and the E_R was enhanced from 25 to 56% at the beginning of the second cycle as the feed flow rate increased from 0.017 to 0.076 m/s. The UF process with perlite added showed the same trend. For the other, the addition of perlite showed obvious effects on E_R and J/J_0. What's more the effect of perlite addition related with the feed flow rate. When the feed flow rate was 0.055 m/s, the E_e increased by 8 and 7%, while the E_R enhanced by 10 and 25% in the second and third cycle separately, compared to the UF process without perlite. As for the process with feed flow rate of 0.017 and 0.076 m/s, the E_R was a bit lower than that with feed flow rate of 0.055 m/s.

The effect of feed flow rate is important in a membrane filtration process because a higher flow rate can reduce membrane fouling by providing a shear force to sweep away deposited materials [27], this explained why, although more wastewater was treated in a given cycle, the resistance of cake layer only increased marginally.

Membrane filtration resistance model was adopted to analyze the reason of the results. The filtration resistances during these UF processes were calculated according to the method introduced before, and the results were listed in Table 7.

The results in Table 7 showed that, in the case of 0.017 and 0.055 m/s flowing velocity adopted, all of the resistances for the processes without perlite were the highest. However, when the perlite presented, two kinds of resistances were considerably reduced. Nevertheless, when increasing the feed flow rate to 0.076 m/s, nearly all of the resistances were considerably increased compared to that of UF process without perlite.

The results indicated that the concentration polarization effect could be minimized by operating at high feed flowing velocities, which led to higher permeate

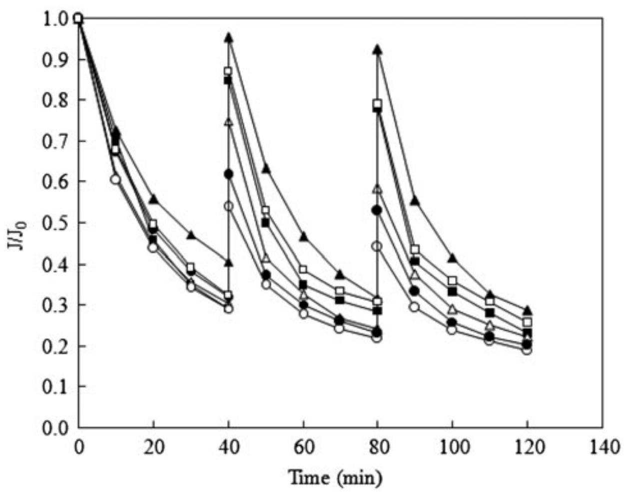

Fig. 7. Effect of feed flowing velocity on the normalized flux during the UF process.

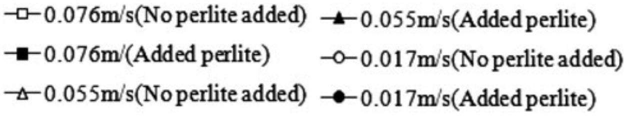

Table 6
The variation of flux in the three cycles of UF with different feed velocities

			E_b	E_R	E_e	E_D (%)
The first cycle	0.017 m/s	UF	1.00	—	0.29	71
		UF + 8.0 g perlite	1.00	—	0.32	68
	0.055 m/s	UF	1.00	—	0.31	69
		UF + 8.0 g perlite	1.00	—	0.41	59
	0.076 m/s	UF	1.00	—	0.31	69
		UF + 8.0 g perlite	1.00	—	0.29	71
The second cycle	0.017 m/s	UF	0.54	25%	0.22	32
		UF + 8.0 g perlite	0.62	30%	0.23	39
	0.055 m/s	UF	0.75	45%	0.24	51
		UF + 8.0 g perlite	0.96	55%	0.32	64
	0.076 m/s	UF	0.87	56%	0.31	56
		UF + 8.0 g perlite	0.85	56%	0.29	56
The third cycle	0.017 m/s	UF	0.44	22%	0.19	25
		UF + 8.0 g perlite	0.53	30%	0.20	33
	0.055 m/s	UF	0.59	35%	0.22	37
		UF + 8.0 g perlite	0.92	60%	0.29	63
	0.076 m/s	UF	0.79	48%	0.26	53
		UF + 8.0 g perlite	0.78	49%	0.23	55

Table 7
Effect of feed flowing velocity on the filtration resistances of the UF process

Resistance		R/R_m	R_c/R_m	R_o/R_m
0.017 m/s	UF	3.28	1.43	0.77
	UF + 8.0 g perlite	2.94	1.21	0.66
0.055 m/s	UF	3.17	1.83	0.33
	UF + 8.0 g perlite	2.35	1.26	0.09
0.076 m/s	UF	3.10	1.81	0.29
	UF + 8.0 g perlite	3.27	2.03	0.24

flux, as showed in the Fig. 6. However, too high flowing velocity might make it difficult for filter aid to adhere on membrane surface. Therefore, the "rigid bridge" structure of the perlite would be weakened and unable to give a full play of the filter aid effect. To conclude, it is important to choose a flowing velocity which can balance the increase in flux with the increase in filter aid efficiency. In our research, 0.055 m/s is the optimal one.

4. Conclusions

In the UF process, the membrane fouling could be limited by adding perlite filter aid to control the structure of the cake layer. The addition of perlite in UF process could enhance the initial flux, alleviate E_D and increase E_R. The particle size and dosage of the perlite had a close relation with the filter aid assisted UF process. The addition of 8.0 g perlite (100–150 μm) could make the E_e enhanced 5% after three cycles compared with UF process without perlite and the E_c enhanced about 9% compared with UF process without perlite.

The traditional operation parameters of the UF such as the TMP and the feed flowing velocity would affect the filter aid assisted UF process by affecting the adhesion of the filter aid agent as well as the structure of the cake layer on the membrane surface. The operating condition of 0.075 MPa and 0.055 m/s could balance the increase in flux with the increase in filter aid effect and the highest J/J_0 and E_R was obtained. When operated at the optimized conditions (0.075 MPa and 0.055 m/s), the E_e was increased by 7% and the E_R was enhanced by 25% compared with UF process without perlite.

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Symbols

J	—	membrane specific flux (kg/m^2 h)
J_0	—	initial membrane specific flux (kg/m^2 h)
S	—	membrane area (m^2)
t	—	time (h)
E_R	—	flux recovery rate
E_e	—	J/J_0 at the end of each cycle
E_c	—	J/J_0 after oscillation cleaning
E_D	—	flux decline rate
E_b	—	J/J_0 at the beginning of cycle
ΔP	—	transmembrane pressure (MPa)
μ	—	viscosity (Pa s)
J_w	—	pure water flux (kg/m^2 h)
R	—	total resistance (m^{-1})
R_m	—	the resistance of membrane (m^{-1})
R_c	—	the resistance of cake layer (m^{-1})
R_o	—	the resistance of contaminants (m^{-1})

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