



Reverse osmosis concentrate treatment by a PAC countercurrent four-stage adsorption-MF hybrid process – a pilot-scale study

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ABSTRACT

A pilot-scale powdered activated carbon (PAC) countercurrent four-stage adsorption–microfiltration (MF) hybrid process was developed to remove organics from reverse osmosis concentrate (ROC). The main focus of this study was to remove the organic matters and prepare qualified influent with lower turbidity and silt density index (SDI) to reverse osmosis (RO) system for further desalination. The results indicated effective removal of organic pollutants from ROC with effluent values that met the requirements for RO influent. The average values of turbidity and SDI in the effluent were 0.70 NTU and 2.52, respectively. The average dissolved organic carbon (DOC) removal rate was approximately 70% when the PAC dosage was between 0.35 and 0.45 g/L. Membrane fouling under two operational modes was analysed and compared, and membrane fouling was reduced in mode II operation. Mode II operation performed better in terms of a shorter hydraulic retention time and lower membrane fouling rate, resulting in more economical and effective operation. UV_{254} and DOC were linearly correlated for both the influent and effluent, and the removal rate of the DOC and PAC dosage also exhibited linear correlation with a linear coefficient $R^2 > 0.95$, which can be used to adjust the PAC dosage during operation.

Keywords: Reverse osmosis concentrate; Powdered activated carbon; Countercurrent adsorption; Microfiltration; Pilot-scale study

1. Introduction

Advanced treatment technology based on the reverse osmosis (RO) process is effective in removing organic and inorganic pollutants contained in biochemically treated effluent leading to the generation of stable and high-quality effluent with increased recovery [1]. Therefore, the technique is widely used in municipal and industrial wastewater treatment and recycling and other fields [2–4]. However, 25%–50% reverse osmosis concentrate (ROC) is generated along with the 50%–75% high-quality reclaimed water gained from the wastewater by the RO technique [5], and the ROC usually contains the following organic matter: refractory dissolved organic materials, endocrine disrupters, anti-scale agents, soluble microbial products, bacteria, and pathogens [6–8]. However, if the ROC

is discharged directly without any treatment, it can severely pollute the receiving body of water and wastewater resources.

The treatment methods for ROC include (1) traditional coagulation/flocculation settling, which typically uses aluminium or ferric salt as a flocculant [5,9–11]; (2) advanced oxidation processes such as ozone, hydrogen peroxide and ozonation under UV radiation [12–14]; (3) electrochemical oxidation [8,15,16]; and (4) adsorption using activated carbon (AC), including powdered activated carbon (PAC) and granular activated carbon (GAC) [12,17]. Among these approaches, adsorption with AC is a well-established technology that is widely used in wastewater purification and exhibits high depuration efficiency and the possibility of regeneration [18]. Compared with GAC, PAC exhibits better thermodynamic and kinetic characteristics that can be used to reduce irreversible microfiltration (MF) membrane fouling and minimize the frequency of chemical cleaning at the appropriate concentration [19]. Our previous work demonstrated

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that at a lower PAC dosage, PAC adsorption combined with MF separation can satisfactorily remove organic matter from ROC and provide qualified influent to the RO system [17]. A lab-scale PAC accumulative countercurrent two-stage and four-stage adsorption-MF hybrid process to treat ROC has also been investigated [20,21]. However, the membrane fouling performance under two operational modes using PAC countercurrent four-stage adsorption-MF in a larger scale facility was not studied. Meanwhile, to deal with the influent with a fluctuated quality, determination of PAC dosage was another challenge.

To further investigate the practical operability of this process on the basis of laboratory research, a pilot-scale study of the PAC countercurrent four-stage adsorption-MF hybrid process for treatment of petrochemical ROC was performed. This study focused on the removal of organics under two operational modes and their influences on the membrane fouling rate. The correlation between UV_{254} and dissolved organic carbon (DOC) in the raw ROC and the effluent, the removal rate of DOC and PAC dosage were analysed.

2. Materials and methods

2.1. Experimental procedure

2.1.1. The pilot-scale device

The pilot-scale device, schematized in Fig. 1, is similar to that reported by Wei et al. [21]; a photograph of the experimental device installed in a plant is shown in Fig. 2.

Reactors A and B were constructed from carbon steel; the reactor parameters under two operational modes are given in Table 1. The upper part of reactor A was a cylinder, and the lower part was a cone with a waste PAC discharge mouth at the bottom. The upper part of reactor B was a long column, the middle part was a square column and the lower part was a square cone with a loaded PAC discharge mouth at the bottom. Six pieces of a hollow fibre membrane module constructed from polyvinylidene fluoride, provided by



Fig. 2. Photograph of the device in the plant.

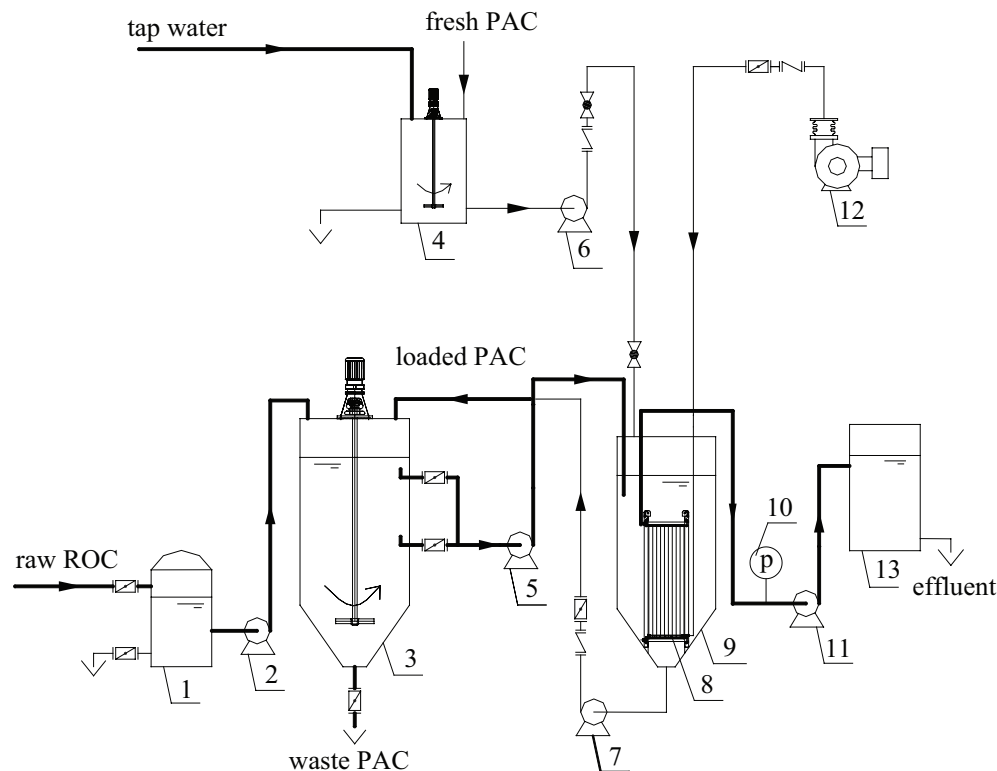


Fig. 1. The device of PAC countercurrent four-stage adsorption-MF hybrid process for pilot-scale study. (1) Raw ROC tank; (2) raw ROC feed pump; (3) reactor A (4) tank for fresh PAC suspension; (5) effluent pump of reactor A; (6) pump for PAC dosing; (7) loaded PAC transfer pump; (8) MF module; (9) Reactor B; (10) vacuum gage; (11) effluent pump of reactor B; (12) air blower; (13) effluent tank.

Table 1
Reactor parameters

Operational mode	Effective volume (m ³)		HRT (h)
	Reactor A	Reactor B	
I	3.00	1.20	6.17
II	0.98		3.69

Memstar Membrane Technology Ltd. (Mianyang, Sichuan, China), were submerged in reactor B. The area of each membrane module was 12.5 m², and the membrane pore size was 0.22 μm. The membrane modules were immersed in reactor B, and continuous aeration with a density of 10 m³/h was provided by a perforated pipe sparger set under the membrane module for mixing PAC with ROC and controlling membrane fouling.

2.1.2. Operational modes of the pilot-scale study

As shown in Fig. 1, the system consisted primarily of reactors A and B. In the countercurrent adsorption process, the adsorption stage was defined in accordance with the flow direction of raw ROC in the system. Raw ROC first entered reactor A to undergo stages 1 and 2 adsorption and then flowed into reactor B to undergo stages 3 and 4 adsorption. Operation was automatically controlled by a programmable logic controller.

Raw ROC was introduced into reactor A; the first-stage adsorption used the original loaded PAC in this reactor, and the second-stage adsorption used the PAC which was finished stages 3 and 4 adsorption discharged from reactor B. After the stage 2 adsorption completion, the mixed liquor in reactor A was separated by gravitational sedimentation, and the supernatant in reactor A was pumped to reactor B three times (mode I operation) or one time (mode II operation). Third-stage adsorption was carried out with the loaded PAC originating in reactor B; after adsorption completion, the aerator was stopped to allow the loaded PAC to settle to the bottom. The suspension with loaded PAC was delivered to reactor A, and the fresh PAC suspension was added by the pump, stage 4 adsorption occurred, and the final effluent was drawn through the MF module.

Fresh PAC entered the system by dosing to reactor B and was used in stages 4 and 3 adsorption sequentially. After the last feeding to reactor B, and the stage three adsorption was completed sequentially, the aerator was stopped and the loaded PAC was settled for 10 min to the bottom of reactor B. Then the loaded PAC was transferred to reactor A through the valve located on the bottom of reactor B and was used in stages 2 and 1 adsorption sequentially [21].

According to the PAC adsorption kinetics study, equilibrium could be reached within 20 min [17]; therefore, the adsorption time of each stage was set to 20 min. ROC and PAC contact was provided by mechanical stirring in reactor A. The settling time for the separation of loaded PAC and treated ROC in the reactor A was 10 min. The final effluent was drawn for 8 min from the MF module with 2 min pause and repeated in this manner until the low water level in reactor B was reached.

To prevent the loaded PAC in the bottom of reactor A from being conveyed to reactor B, the liquid containing

loaded PAC with a volume of approximately 0.50 m³ (mode I operation) and 0.52 m³ (mode II operation) remained in reactor A. Similarly, to ensure submersion of the MF membrane, the final effluent with a volume of 0.43 m³ remained in reactor B. The membrane flux was approximately 25 L/h·m² in both mode I and II operations when the effluent was drawn.

2.2. Theory and calculation

The equilibrium amount of DOC adsorbed on PAC (mg/g) (i.e., q_e) is calculated by Eq. (1):

$$q_e = \frac{C_o - C_e}{m/V} \quad (1)$$

where V is the volume of ROC (L); C_o and C_e are initial and equilibrium concentrations of DOC in ROC (mg/L), respectively; and m is the PAC dose (g).

Our previous research demonstrated that PAC adsorption used in the ROC treatment closely followed the Freundlich adsorption isothermal, as shown in Eq. (2) [17]:

$$q_e = k_f C_e^{1/n} \quad (2)$$

where k_f is the Freundlich capacity factor (mg^(1-1/n)·L^{1/n}/g); and $1/n$ is Freundlich intensity parameter. In the adsorption isotherm experiment, because the organic concentration in raw ROC fluctuated daily, the adsorption experiment was performed several times; the average values of k_f and $1/n$ were 7.74 and 0.55, respectively.

The specific flux (SF) of membrane is the flux at a standard temperature divided by the transmembrane pressure (TMP) and the definition is shown as Eq. (3) [21].

$$SF = \frac{J_0(1.03)^{(20-T)}}{TMP} \quad (3)$$

where SF is the specific flux of membrane at 20°C (L/(m²·h·mH₂O)); J_0 is the flux measured at water temperature (L/(m²·h)); T is the water temperature (°C); TMP is the transmembrane pressure (mH₂O).

To compare the membrane fouling rate in the two operational modes, the parameter γ was defined as the reduction of SF after a water column with unit length passes through the membrane, as shown in Eq. (4), which is the same as that reported by Wei et al. [21]:

$$\gamma = \frac{SF_o - SF_f}{V_t/A} \quad (4)$$

where SF_o and SF_f are the initial and final SF (L/(m²·h·mH₂O)), respectively; V_t is the volume of cumulative effluent treated (m³); and A is the membrane surface area (m²).

2.3. Analytical methods

The DOC of the raw ROC and the effluent was determined using a TOC analyser (TOC-VCPH, Shimadzu, Japan). The absorbance at 254 nm (UV₂₅₄) was analysed using a TU-1810 UV/Vis spectrophotometer (Persee, Beijing, China). COD analyses were performed in accordance with

the standard methods for water and wastewater analysis [22]. The pH value was measured by a professional meter (PP-20, Sartorius, Germany). Turbidity was measured by an optoelectronic turbidity instrument (2100P, HACH, USA); SDI was measured by using the standard method [23].

2.4. Materials

The ROC was taken from an ultrafiltration (UF) membrane bioreactor-RO process in a refinery wastewater treatment plant. The characteristics of the ROC are presented in Table 2.

PAC (200 mesh) supplied by Yunguang Co. Ltd. (Datong, China) was used for this study. Its total surface area was 826.0 m²/g, the minimum iodine value was 735 mg/g, the methylene blue value was 130 mg/g and the maximum ash content was 18.0%. All PAC characteristic data were provided by the manufacturer.

3. Results and discussion

3.1. Comparison of process performance at different operational modes

Because the organic concentration of raw ROC are constantly fluctuating and cannot be accurately predicted, the PAC dosage must be adjusted along with the changes of influent during operation. To investigate the performance of the process, the experiment was carried out continuously about 25 d for each operational mode and about 7 d with a constant PAC dosage. Different PAC dosage levels were investigated in terms of effluent quality and the degree of membrane fouling for each operation mode.

3.1.1. The removal of organics from ROC

Based on the monitoring report over an extended time provided by the plant, the DOC of raw ROC was in the range of 22–50 mg/L. The requirement for RO influent in terms of DOC concentration lay in the range of 9–16 mg/L [24]; therefore, in the pilot-scale experiment, the target effluent DOC concentration was set in this range. The effect of PAC dosage on organic removal under two operational modes was studied by adjusting the PAC dosage from 0.15 to 0.45 g/L.

Table 2
Characteristics of the ROC

Parameter	Value (average value)
Chemical oxygen demand (COD), mg/L	83.33–137.0 (107.9)
Dissolved organic carbon (DOC), mg/L	24.11–48.08 (30.73)
pH	7.79–8.34 (8.12)
Temperature, °C	25–29 (26.2)
Turbidity, NTU	0.6–0.9 (0.7)
Total hardness (as CaCO ₃), mg/L	737.2
Cl ⁻ , mg/L	622.7
NO ₃ ⁻ , mg/L	270.5
SO ₄ ²⁻ , mg/L	340.2

The DOC values of influent and effluent at different operational conditions are presented in Fig. 3. As shown in the figure, the DOC of raw ROC values changed daily. Additionally, although the fluctuation range of the influent was wide, the effluent was relatively stable, which demonstrated that the process was resistance to shock loading.

It can be observed in Fig. 3(a) that under mode I operation during the initial running time when PAC dosage was comparatively low, the organic matter content of effluent was higher and the average effluent DOC value was 17.3 mg/L, which did not meet the requirements for RO influent. The reasons for the higher effluent organic value could be that the PAC dosage was too low to remove sufficient organic material from the ROC.

To improve the effluent quality, the PAC dosage was changed to 0.25 g/L after the first period of the experiment under mode I operation. It can be observed from Fig. 3(a) that the average effluent of the DOC was 15.5 mg/L, which was in the target range and met the requirement to re-enter the RO system. Because the DOC value of the raw ROC tended to increase, the PAC dosage increased to 0.35 g/L. It can be observed from Fig. 3(a) that in the last period of the experiment under mode I operation, the average effluent of DOC was 11.5 mg/L. This satisfactory effluent value resulted from both the increase of PAC dosage and the PAC cake layer formed on the MF membrane surface, which was capable of intercepting organic matter.

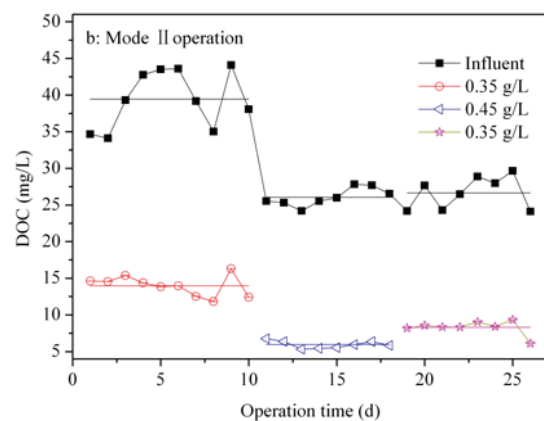
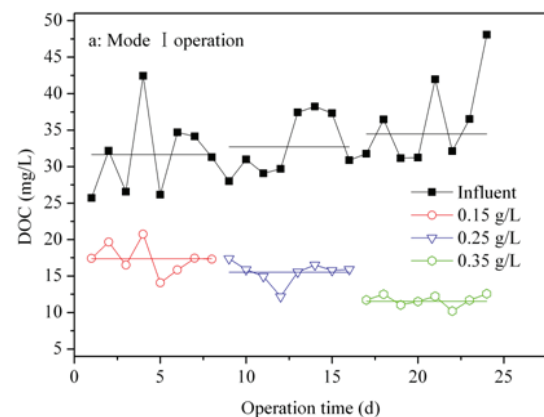


Fig. 3. The DOC of the influent and effluent at two operational modes with different PAC dosage.

Mode II operation was conducted to further explore operational conditions and specifically to reduce the hydraulic retention time (HRT) and membrane fouling. Under this operational mode, the first setting was a 10-day experiment with a PAC dosage of 0.35 g/L; the average DOC effluent was 14.0 mg/L. When the operation completed, the membrane was chemically cleaned due to severe membrane fouling. After cleaning, the experiment was run for 8 additional days with a PAC dosage of 0.45 g/L. During the second period, the organic content of the influent was low, and the effluent DOC value was only approximately 5.94 mg/L; therefore, the PAC dosage was changed to 0.35 g/L again and the experiment continued for 8 additional days. It can be observed from Fig. 3(b) that the DOC in the effluent was low and that the fluctuation was extremely small, especially under the mode II operation that followed mode I. In conclusion, during actual operations, the PAC dosage should be adjusted based on the raw ROC quality to ensure acceptable effluent quality and lower operational cost.

There were two experimental periods with a PAC dosage of 0.35 g/L during mode II operation. The average values of DOC in the influent and effluent were used in the calculations supporting Table 3 and Fig. 4.

Table 3 reports the experimental and calculated organic removal rate (average values) from the ROC with different PAC dosages. The calculation method for organic removal rate is the same as that reported by Wei et al. [21].

It can be observed from Table 3 that the calculated removal rates are higher than the experimental values for

both operational modes, but that the difference is less than 7%. Dialynas and Diamadopoulos [25] have studied for DOC removal with a pilot-scale hollow-fibre UF unit followed by a PAC or GAC adsorption unit. The removal rate of the PAC-UF was 60% and 36% for GAC-UF in the municipal wastewater treatment plant. The results in Table 3 demonstrate that the calculation method is appropriate and that the device investigated in this pilot-scale study is feasible.

According to the data in Table 3, the operational mode has no detectable effect on the removal of organic matter; the DOC removal rates are similar under the two operational modes at the same PAC dosage of 0.35 g/L. However, because mode II operation involves a smaller volume with a shorter HRT, it is beneficial for membrane fouling control as discussed in section 3.1.2 and is preferable for real applications compared with operational mode I.

Fig. 4 shows a comparison of the amount of the DOC adsorbed on PAC at equilibrium with single-stage and four-stage adsorption. The former is labelled as “calculated single-stage operation” and is calculated by Eqs. (1) and (2) using the average influent values in Fig. 3 as C_0 and PAC dosage (m/V); the latter is labelled as “measured four-stage operation” and is calculated by Eq. (1) using the average influent values as C_0 and effluent values as C_e in Fig. 3 at each PAC dosage. It can be observed from Fig. 4 that compared with q_e values in single-stage adsorption, those in four-stage adsorption were one to two times higher, which indicates that four-stage adsorption can effectively increase the adsorption amount and reduce PAC consumption.

Table 3
DOC removal rate (%) at different PAC dosages

Operational mode	Data source	PAC dosage (g/L)			
		0.15	0.25	0.35	0.45
I	Experiment	44.31	51.97	66.25	
	Calculation	51.37	54.34	69.82	
II	Experiment			64.33	77.21
	Calculation			69.73	83.47

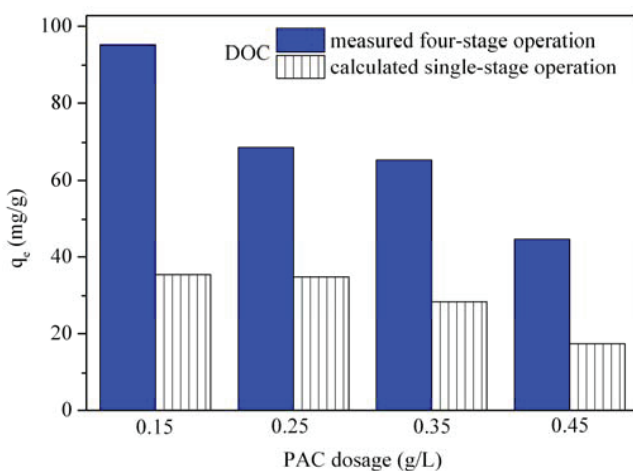


Fig. 4. The q_e value of the DOC for single- and four-stage operation at different PAC dosages.

3.1.2. Analysis of membrane fouling

Membrane fouling is the bottleneck constraining the widespread use of membrane technology. SF is one of the important parameters characterizing MF membrane performance in the experiment. Under the two operational modes, the change in SF values is shown in Fig. 5.

It can be observed from Fig. 5(a) that under mode I operation, the initial SF value (SF_0) of the MF membrane was 16.90 L/m²·h·mH₂O and the final one was approximately 7 L/m²·h·mH₂O. In the initial stage of the experiment, SF values decreased first rapidly, then gradually. This behaviour could be caused by the fact that in the initial stage of this experiment, suspended particles, soluble organic matter and inorganic matter in the ROC with small molecular weight might be adsorbed and deposited in membrane pores. This phenomenon could cause a rapid decrease in the SF value. With increasing operation time, the decrease in SF became more gradual, likely because aeration and induced hydraulic scouring led to a dynamic equilibrium between accumulation and release of the PAC cake layer on the MF membrane surface. Bergamasco et al. [26] also reported that SF curve can be divided into two domains: the first corresponds to the initial flux decline and involves internal fouling, whereas the second corresponds to the smooth decrease and involves external membrane fouling. Additionally, it can be observed from Fig. 5(b) that the SF increased considerably after the first-period operation with a PAC dosage of 0.35 g/L, this behaviour was caused by the chemical cleaning of the membrane as mentioned in section 3.1.1. The SF increased slightly when the PAC dosage was changed from 0.45 to 0.35 g/L;

this result is attributable to the aerator operating for 3 h without drawing effluent, which would cause the cake layer to fall off and the SF to increase.

The reduction of SF under two operational modes was given by γ ($L/m^3 \cdot h \cdot mH_2O$) in Table 4, which presented the effect of different PAC dosages on membrane fouling rate under two operational modes.

It can be observed from Table 4 that under mode I operation, with increasing PAC dosage, γ values increased except at a dosage of 0.15 g/L. Additionally, γ values increased with increasing PAC dosage at both operational modes except at a dosage of 0.15 g/L; this increase could be caused by the increasing concentration of suspended matter in reactor B, which would contribute to a thicker cake layer on the membrane surface. It also can be observed from Table 4 that the γ value under mode II operation was less than that of mode I. We conclude that under mode II operation,

the highest concentration of suspended matters was only one-third that of mode I, which allowed the concentration polarization to weaken and better mitigated membrane fouling. In addition, the HRT of mode II operation was 3.69 h, which was shorter than that of mode I (shown in Table 1). Therefore, in terms of ensuring beneficial treatment, mode II operation performed better by slowing down the rate of membrane fouling, resulting in more economical and effective operation.

3.1.3. Effluent turbidity and SDI

Turbidity corresponds to the amount of colloidal and other suspended material in water. When the turbidity value in the effluent is high, it can be indicative of membrane module damage.

The SDI value determines whether the water can serve as an influent for an RO system. The purpose of this study was to enable effluent after ROC treatment to reach the water quality standard for re-entering the RO system and ensure that the water production of the RO system would be stable; hence, the SDI value was measured. Generally speaking, the SDI value of influent water in an RO system should be less than 5 [27].

The effects of two operational modes on turbidity and SDI were little and could be ignored during the experiment; therefore, Table 5 presents the average turbidity and SDI values of the final effluent under the two operational modes. It can be observed from Table 5 that the average value of turbidity was 0.70 NTU and that the standard deviation was 0.052 NTU.

It can also be observed from Table 5 that the effluent SDI values were all less than 3. This finding indicates that PAC countercurrent four-stage adsorption-MF technology can effectively remove colloids and other suspended solids that can easily foul an RO membrane. Therefore, this technology can ensure that effluent quality meets the influent requirements for an RO system.

3.2. Correlation of DOC, UV_{254} and DOC removal rate and PAC dosage

DOC measurements are generally expensive, whereas UV_{254} measurements are faster, cheaper, and can be performed in situ Wang et al. [20] reported that effluent DOC values are correlated with UV_{254} values. Hence, UV_{254} values can be employed to indirectly characterize the concentration of organics in the water.

The relationship between the DOC and UV_{254} values of the influent and effluent water is shown in Fig. 6. It can be observed from Fig. 6 that for both the influent water and

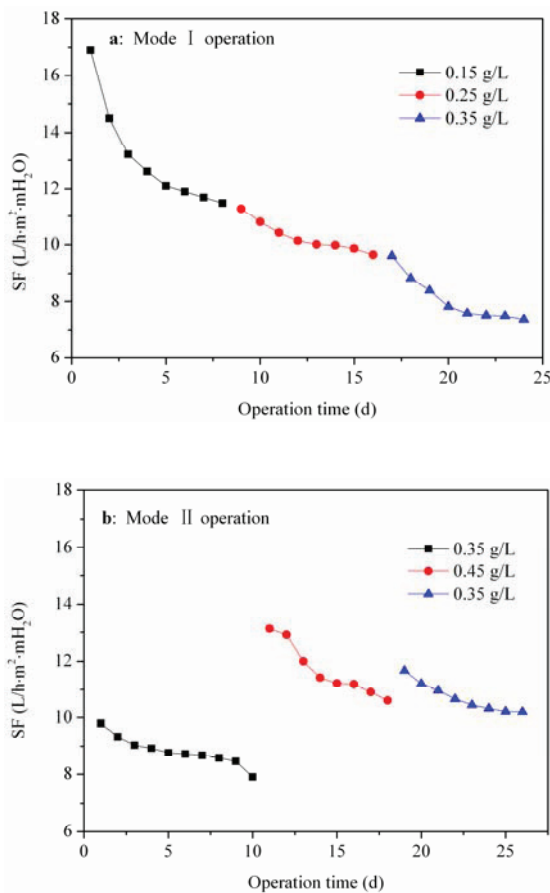


Fig. 5. SF values during operation.

Table 4
The reduction of SF under two operational modes, γ ($L/m^3 \cdot h \cdot mH_2O$)

Operational mode	PAC dosage (g/L)			
	0.15	0.25	0.35	0.45
I	7.36	1.87	2.79	
II			1.39	2.56

Table 5
Average values of turbidity and SDI of the effluent

Parameter	Number of measurements	Average value	Standard deviation
Turbidity (NTU)	60	0.70	0.05
SDI	15	2.52	0.07

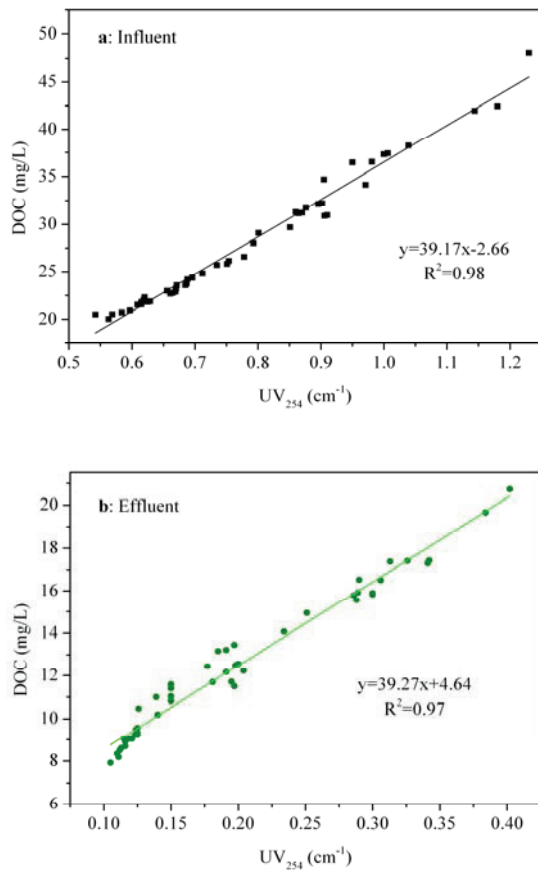


Fig. 6. DOC and UV₂₅₄ correlation in the influent (a) and the effluent (b).

the effluent, UV₂₅₄ and DOC values were linearly correlated, the slopes of the two lines were in good agreement and there was little difference in the intercept. Therefore, DOC values of both the raw ROC and the effluent can be rapidly and effectively calculated through the measurement of their UV₂₅₄ values.

Fig. 7 shows the relationship between DOC removal rate and PAC dosage in the pilot-scale experiments. It can be observed from Fig. 7 that the removal rate of DOC and PAC dosage was also linearly correlated. A rigorous justification for linear correlation is challenging to develop, but the finding can be understood in terms of mass conservation. Using the linear relationships of Figs. 6 and 7, the PAC dosage can be determined after identifying the DOC value. This approach provides a practical method for adjusting the PAC dosage during operation and for guaranteeing effluent quality. Additionally, the linear relationship between DOC and UV₂₅₄ can be used to help estimate the DOC values of the RO influent by measuring UV₂₅₄ to monitor effluent water quality continuously, making the whole process more reliable [19].

An additional experiment was performed to verify the feasibility of estimating the PAC dosage using the relationship between DOC and UV₂₅₄ and the relationship between the PAC dosage and the DOC removal rate. By measuring the UV₂₅₄ value of the raw ROC, the DOC value was calculated from Fig. 6(a), and then the value of the required effluent DOC of 10.0 mg/L was set to allow calculation of the DOC

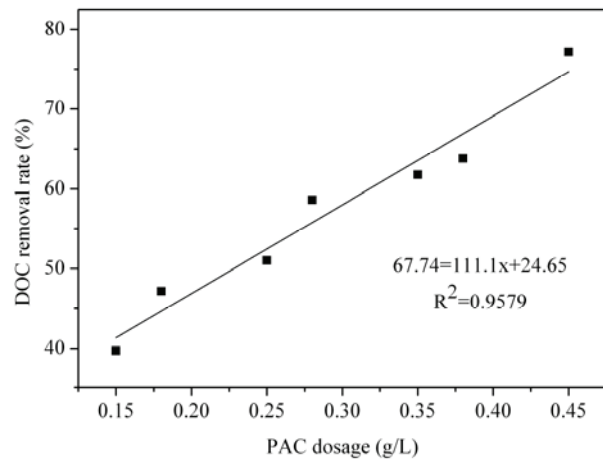


Fig. 7. Relationship between DOC removal rate and PAC dosage.

Table 6
Comparison of estimated and actual experimental values

Data source	DOC (mg/L)		DOC removal rate (%)	PAC dosage (g/L)
	Influent	Effluent		
Estimate	31.0	10.0	67.74	0.39
Experiment	32.0	10.5	67.29	

removal rate. Finally, a PAC dosage was calculated using Fig. 7. This PAC dosage was implemented for 24 h while DOC values in the influent and effluent were measured. A comparison of the estimated and experimental values is shown in Table 6.

Table 6 indicates that the estimated influent DOC value was slightly lower than the experimental one; the former was calculated using the measured UV₂₅₄ value of the raw ROC and the relationship shown in Fig. 6(a). After the PAC dosage was determined by the estimation method, it was used in the experiment. The experimental effluent DOC value was measured three times and the average was reported; this value was slightly higher than the estimated value. There is little difference between the estimated DOC removal rate and the experimental one, and the latter was obtained by the experiment with the estimated PAC dosage. Therefore, the method can be used for roughly estimating the PAC dosage. Additionally, the effluent DOC could also be calculated using the measured effluent UV₂₅₄ and the relation in Fig. 6(b) in the plant to characterize process performance. When the concentration of organic matter in the ROC changes during operation, this estimation method can be used to adjust the PAC dosage to ensure effluent water quality.

4. Conclusions

- The two operational modes can effectively remove organic pollutants from the ROC, and the effluent meets water quality requirements for re-entering the RO system in terms of DOC, turbidity, and SDI, which improves the RO system recovery rate; therefore, the PAC counter-current four-stage adsorption-MF hybrid process offers broad application prospects.

- The q_e values in four-stage adsorption were one to two times higher than in single-stage adsorption, which indicates that four-stage adsorption can effectively increase the adsorption amount and reduce PAC consumption.
- The operational mode has no detectable effect on the removal of organics. The mode II operation has a relatively short HRT, which reduced the capital cost. Additionally, the membrane fouling rate is lower in this operational mode.
- The UV_{254} and DOC exhibit good linear correlation, and a good correlation also exists between the DOC removal rate and PAC dosage with a linear coefficient $R^2 > 0.95$. These linear correlations were used to adjust the PAC dosage online, which met the requirement for the effluent and simultaneously reduced operating costs.

Acknowledgments

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