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Performance evaluation of a polyethersulfone composite ultrafiltration membrane for oily wastewater purification

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ABSTRACT

The amount of substation accident oil pool wastewater (SAOPW) generated has been increasing due to the successive addition and renovation of substations, and the discharge of untreated or incomplete treatment outside the station will cause serious environmental pollution problems. In this study, a polyethersulfone (PES) composite ultrafiltration membranes were fabricated using phase inversion method and evaluated them for oil removal from SAOPW. The morphology and functional groups of PES composite membranes before and after filtration were characterized and compared through scanning electron microscopy and Fourier-transform infrared spectroscopy. The effects of operating pressure, feed temperature, initial oil concentration and operating time were systematically investigated using flux recovery and oil removal rate as the indexes of investigation, and the process economy was studied and evaluated. The results showed that the PES composite membrane had a relatively high-water flux of 260.2 ($L\cdot m^{-2}\cdot h^{-1}$) and a high oil removal rate (≥90%), which could effectively remove oil from water. Besides, its high flux recovery ratio (≥90%) after four filtration and cleaning cycles indicated the excellent performance of this PES composite membrane in the separation of oil–water emulsions. This study confirms the applicability of PES composite membrane for oil removal from SAOPW, providing a promising treatment method for the SAOPW treatment.

Keywords: Substation accident oil pool wastewater (SAOPW); Polyethersulfone composite ultrafiltration membrane; Operating conditions; Membrane fouling; Separation performance

1. Introduction

The oily wastewater in the transformer accident oil pool comes from the oily wastewater in the accident oil pool formed by the mixing of transformer waste oil with rainwater during the daily operation and maintenance of the transformer due to oil leakage faults. The wastewater is often collected in the emergency oil pool near the substation, also known as substation accident oil pool wastewater (SAOPW). Transformer oil is mainly composed of mineral oil, which is a complex mixture of hydrocarbon groups, including alkanes, cycloalkane and aromatics [1]. Most of these components are difficult to degrade, toxic and easily carcinogenic. Direct discharge into the natural environment without treatment or incomplete treatment will cause serious harm to the ecological environment and human health. In order to create a green ecology and promote sustainable development, the treatment of SAOPW is imperative [2].

Currently, the mainstream oily wastewater treatment technology includes ultrafiltration (UF) process [3,4], membrane bioreactor [5], coagulation/flocculation [6], adsorption method [7], coalescence separation [8] and electrocatalytic

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oxidation method [9]. Compared with conventional separation technologies such as coagulation, air flotation, coagulation, oxidation, the UF membrane separation is regarded as a reliable and green separation technology for wastewater treatment for its high separation efficiency, wide practicability, simple operation and avoidance of secondary pollutants, which can intercept more than 90% of emulsified oily wastewater when used alone, and is widely used in petroleum production, chemical industry and other industrial activities [10–12].

UF membranes with high water flux and separation efficiency are very necessary. But a trade-off between membrane permeability and selectivity that lowers oil rejection is one of the most technical challenges in the separation industries [13]. Utilizing organic polymers such as polyethersulfone (PES) [14], polyvinylidene fluoride (PVDF) [15] and polyvinyl chloride (PVC) [16] in mixed matrix membranes is preferable. Among all the aforementioned polymers, PES membrane is renowned for its excellent mechanical stability, chemical resistance, and heat resistance [14,17]. However, PES ultrafiltration membranes also have some drawbacks, such as a tendency to fouling and intrinsic hydrophobic nature, which have limited the application of PES in oily wastewater treatment [14,17]. The defects caused by the hydrophobicity of PES polymer materials have been investigated and modified to enhance hydrophilicity and improve separation efficiency and service life [11,14]. Ouda et al. [18] prepared iron oxide-modified kaolin nanocomposites (Fe-HNC) by solvothermal method and doped Fe-HNC nanocomposites into PES matrix to prepare ultrafiltration membranes with good anti-contamination properties. Arumugham et al. [19] successfully prepared PES composite membranes with high permeation flux and good anti fouling performance using non-solvent induced phase separation technology.

Up to now, few studies have involved the application of ultrafiltration membranes for the treatment of SAOPW. In this study, a PES composite ultrafiltration membrane was synthesized and applied to its actual SAOPW wastewater to explore its permeability, separation performance and anti-fouling performance, which provides a new solution for the treatment of SAOPW.

2. Materials and methods

2.1. SAOPW wastewater

The SAOPW wastewater was obtained from Zaoyuan substation station located in central China. Table 1 shows the characteristics of the SAOPW.

2.2. Chemicals

The chemical reagents used in the experiments were of analytical grade. N,N-Dimethylacetamide (DMAc, ≥99.0%), polyvinylpyrrolidone (PVP, MW 40,000), sodium sulfate anhydrous, sodium hydroxide, hydrochloric acid (HCl, 36%~38%) were obtained from Sinopharm Chemical Reagent, China. The solvent such as tetrachloroethylene (~99.8%) was purchased from Shanghai Aladdin Biochemical Technology Co., China. Deionized water was obtained by a water purification system (Milli-Q Academic, Merck Millipore, Darmstadt, Germany), with the electrical conductivity less than 0.055 $\mu S\cdot cm^{-1}$. Polyester non-woven fabric (NWF, 100 $g\cdot m^{-2}$, Shandong Hengrui Tong [HRT] New Materials Engineering Co., Ltd., China).

2.3. PES composite membrane preparation

Phase inversion method was used for membrane fabrication. Firstly, the PES resin, PVP powder was fully dissolved in DMAc under strong mixing at 80°C for 6 h to increase the uniformity, and then the casting solution was ultrasonically defoamed for 2 h, and the composition of the casting solution, 18 wt.% PES, 1 wt.% PVP, and 81 wt.% DMAc was obtained [14]. Secondly, the non-woven fabric was first ultrasonically cleaned with ethanol and distilled water for 3 times, and then dried in an oven at 60°C for 12 h for use. Finally, the obtained casting solution was scraped into the non-woven fabric with a thickness of 150 μm, and then the cast membrane was immediately immersed in a water bath at 40°C for phase inversion. The virgin membrane was taken out and dried in oven at 60°C for 4 h.

2.4. Analytical methods

The concentration of chemical oxygen demand (COD), oil content and turbidity in SAOPW wastewater were measured according to our previous literature [3]. A scanning electron microscopy (SEM, MIRA LMS, TESCAN, Czech) was used to obtain the surface morphology of fouled ceramic membrane. The Fourier-transform infrared spectroscopy (FTIR) of PES composite membranes were scanned using Nicolet iS10 FTIR Spectrometer (Thermo Nicolet Corp., Madison, WI, USA). The viscosity of the feed was determined by a digital viscometer (NDJ-5s, China). Contact angles were obtained on a contact angle goniometer (JC2000D, China) using the sessile drop technique, as described by Li et al. [17].

2.5. Filtration experiments

The experimental set-up used in the dead-end UF set up is presented in Fig. 1. The UF membrane system consists of an ultrafiltration cup (Bonabio Company, China), an electronic balance (BSA2202, Saturis, Germany), a nitrogen bottle and a pressure reduction valve. First, the 500 mL oily wastewater sample was added to the ultrafiltration cup, and the constant pressure was provided by the nitrogen bottle to enable the solution to penetrate the UF membrane. The cumulative weight of the penetrate flowing into a beaker

Table 1
Characteristics of wastewater used in the experiments

Parameter	Raw wastewater
pH	6.8
Oil, $mg\cdot L^{-1}$	46.1
COD_{Cr}, $mg\cdot L^{-1}$	650.1
NH_3–N, $mg\cdot L^{-1}$	7.5
Turbidity, NTU	125
Conductivity, $\mu S\cdot cm^{-1}$	863

placed on an electronic balance was continuously measured by the balance, and the penetrate mass/time data during an experimental run were collected and recorded, respectively. The self-fabricated PES composite membrane (reasonable membrane area is 31.65 cm^2) was employed to evaluate the permeability and rejection coefficient of membrane. The UF membrane is placed at the bottom of the ultrafiltration cup, and the retentates are trapped at the surface of the UF membrane. To reduce the effect of concentration polarization on the membranes surface, the magnetic stirrer was applied at 300 rpm. After that, the pressure driven by a nitrogen bottle was adjusted at 1 bar for obtaining constant pure water flux.

In the process of experiment, the permeate flux J (L·m^{-2}·h^{-1}) of UF membrane was determined by Eq. (1) [20]:

$$J = \frac{Q}{A \times \Delta t} \quad (1)$$

where Q (L) is the volume of permeate, A (m^2) denotes the effective filtration area, Δt (h) represents the time interval.

The removal rate R (%) of oil and COD was determined by Eq. (2) [21]:

$$R = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \quad (2)$$

where C_p (mg·L^{-1}) and C_f (mg·L^{-1}) are the concentrations of oil or COD in permeate and feed stream.

The membranes were fouled by repeated cycles of filtration using deionized water washing followed by chemical backwashing. When the membrane flux is reduced by 10%–20%, deionized water is used for rinsing the residues for 3 min. when the membrane flux is reduced by more than 30%, chemical cleaning was carried out in 0.1 M NaOH solution, 0.1 M HCl solution, and then rinsed with deionized water and permeate flux was measured. The membrane flux recovery ratio (F_r) is used to reflect the anti-fouling ability of the membrane, and the solution is used as the test solution. The specific operation process is as follows:

The membrane flux recovery ratio (F_r) was described by Eq. (3) [20]:

$$F_r = \left(\frac{J_1}{J_0}\right) \times 100\% \quad (3)$$

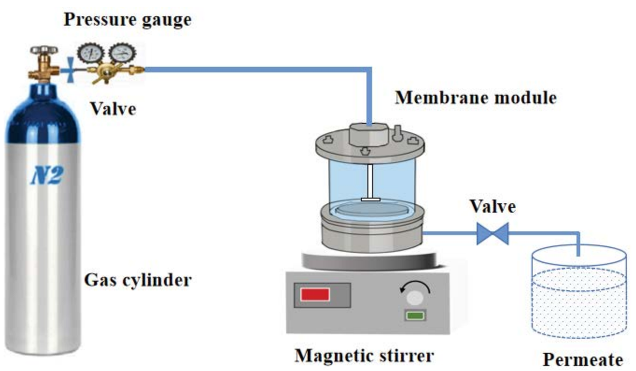

Fig. 1. Schematic of the ultrafiltration set-up.

where F_r (%) is the flux recovery ratio of the membrane, J_1 (L·m^{-2}·h^{-1}) is pure water flux after membrane cleaning, J_0 (L·m^{-2}·h^{-1}) is pure water flux before membrane cleaning.

3. Results and discussion

3.1. Effect of operating pressure

The pure water flux of the prepared PES composite membrane at 0.1 MPa and 25°C is 260.2 L·m^{-2}·h^{-1} and the contact angle is 65.7°, lower than the pure PES membrane, contact angle (68.5°), indicating the dosing PVP in the casting solution is beneficial to improve the hydrophilicity of the membrane. Operating pressure is the main driving force for UF membrane filtration, and it is one of the important factors affecting the membrane flux and oil retention rate of the membrane. If the operating pressure is too low, the flux of the membrane is relatively low; if the pressure is too high, the power consumption will also increase, thereby increasing the operating cost. Fig. 2 shows the changes in the influence of different operating pressures on the membrane flux and oil removal rate of SAOPW wastewater.

It can be seen from Fig. 2 that within a certain range, the membrane flux increases with the increase of operating pressure, while the rejection rate is opposite. When the operating pressure is below 0.2 MPa, the membrane flux increases significantly; when the operating pressure is greater than 0.2 MPa, the membrane flux increases slowly, which is due to the influence of concentration polarization. Generally speaking, the membrane flux of UF membrane will increase with the increase of operating pressure, but when the permeate flux exceeds its critical value, the further increase of operating pressure will intensify the concentration polarization, thicken the gel layer and increase the resistance of the gel layer, which hinders the increase of membrane flux [13,14,16]. It can also be seen from Fig. 2 that the removal rate is inversely proportional to the operating pressure and decreases with the increase of pressure, but the removal rate of oil is always above 90%. Possible reason is that some oil droplets are squeezed through the membrane pores along with the permeate as the operating pressure increases, but

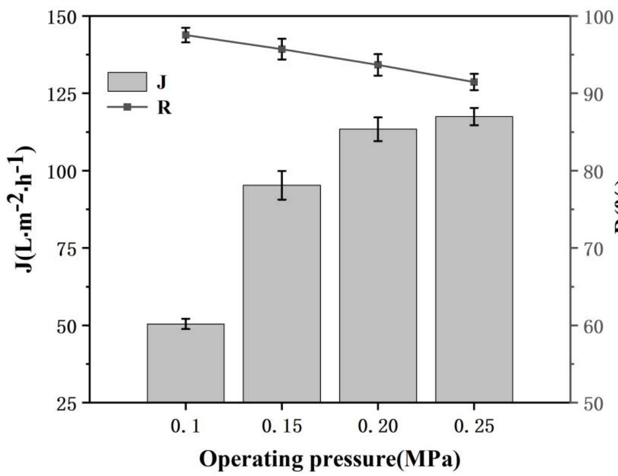

Fig. 2. Effect of the operating pressure on the permeate flux and oil removal rate.

very few oil droplets are able to pass through the membrane due to the existence of size distribution of membrane pores and oil droplets and concentration polarization due to increase in retentate concentration [22].

3.2. Effect of feed temperature

Fig. 3 shows the effect of the feed temperature on permeate flux and oil removal rate at an operating pressure of 0.1 MPa with an oil content of 100 mg·L^{-1}. It can be seen from Fig. 3 that the PES composite membrane flux increases gradually with the increase of temperature, and the increase range of membrane flux at the feed temperature of 25°C–40°C is larger than that at 10°C–25°C. The reason is that the viscosity of the solution gradually decreases with the increase of temperature, improving the mass transfer efficiency of the solution, thereby increasing the water flux of the ultrafiltration membrane [23]. In addition, the experimental results also showed that the apparent viscosity of the feed decreased from 1.12 to 0.85 mPa·s as the temperature was increased from 25°C to 40°C. The oil retention in the graph decreases with increasing temperature, but the retention remains above 94%, probably because the swelling of the intrinsic polymer membrane and the diffusion of molecules in the feed liquid increase with increasing temperature; at the same time, the effect of temperature polarization makes the removal rate of the membrane decrease [24,25]. Considering industrial practical case, the feed temperature should be kept above 25°C.

3.3. Effect of oil initial concentration

The oil concentration in the SAOPW was varied from 10 to 100 mg·L^{-1}, keeping all other parameters constant: operating pressure 0.1 MPa, temperature 25°C and run time 15 min. Fig. 4 presented that the PES composite membrane flux decreased with the increase of oil initial concentration, while the oil removal rate increased. It can be clearly seen that when the initial feed concentration of oil is lower than 40 mg·L^{-1}, the increase trend of oil removal rate is more obvious. This can be explained that when the initial oil content in the feed liquid increases, the clogging of the membrane pores of the PES composite membrane also increases, and at the same time, the gel layer formed on the membrane surface becomes thicker, and the driving force for the solvent to penetrate the membrane surface of the UF membrane weakened, leading to a decrease in permeate flux [3,17]. Within the feed oil concentration range, the oil removal rate increases rapidly with the initial oil concentration and then slows down. The concentrations of Oil, COD_{Cr} and NH_3–N in permeate could meet the corresponding standard requirements of the "Integrated Wastewater Discharge Standard of China (GB8978-96)". The results were shown in Table 2.

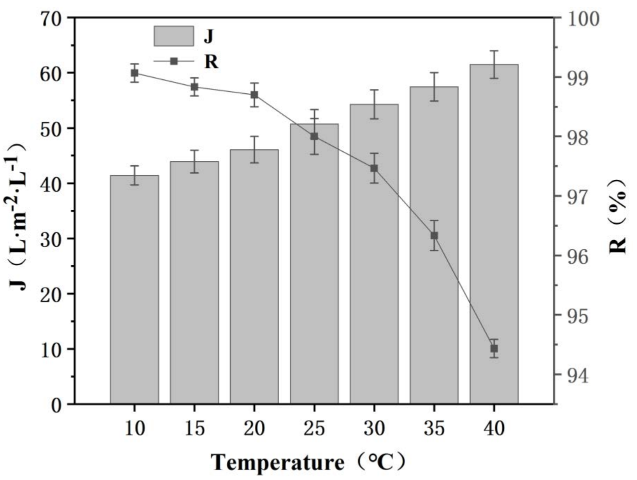

Fig. 3. Effect of the feed temperature on the permeate flux and oil removal rate.

3.4. Effect of cleaning on membrane characteristics

3.4.1. Surface morphology

Scanning electron micrographs of the surface and cross-sectional morphology of the PES composite membranes used in this study are presented in Fig. 5. The SEM images of a virgin and fouled membranes are compared in Fig. 5. The virgin membrane surface was observed to be highly porous with surface pore size in the range of approximately 0.2 μm (nominal MWCO ~ 500 kDa). Due to the deposition of the fouling cake/gel layer on the fouled membrane surface, the surface pores were not visible in SEM micrographs (Fig. 5B). As presented in the Fig. 5C, cross-section images

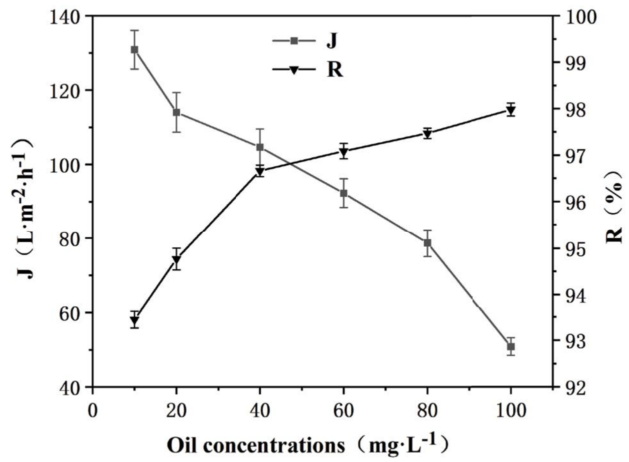

Fig. 4. Effect of the feed concentration on the permeate flux and oil removal rate.

Table 2
Main wastewater parameters of the permeate monitored (unit: mg·L^{-1})

Parameter	Permeate	Discharge Standard of China (GB8978-96)
pH	6.8	6~9
Oil	3.5	10
Chemical oxygen demand	73	100
NH_3–N	0.45	1.0
Turbidity	3.4	—

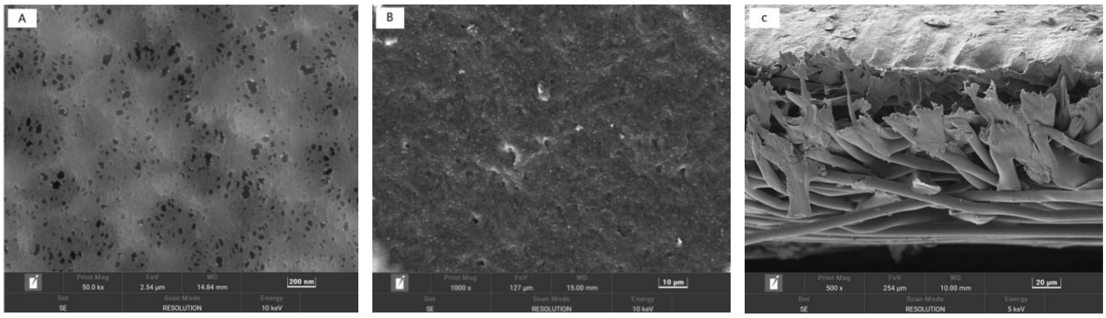

Fig. 5. Scanning electron microscopy images of polyethersulfone composite membrane: (A) virgin membrane surface, (B) fouled membrane surface, and (C) cross-section.

exhibited clearly that a homogeneous dense skin layer was coated on a woven fiber support layer and the thickness of PES composite membrane was about 150 μm.

3.4.2. FTIR analysis

The FTIR spectra were applied to verify the functional groups of organic materials depositing on the membrane surface. When a membrane was fouled, the FTIR peaks of the virgin membrane were changed in absorbance intensity, indicating the covering of the original clean surface by functional groups of foulants [25]. Fig. 6 exhibited the spectra of the top surface of virgin and cleaned membranes. As shown in Fig. 6a, a broad band around 3,430 cm^{-1} was attributed to O–H stretching frequency, due to absorption of moisture on the membrane. Peak at 2,957 cm^{-1} band corresponded to the stretching vibration of C–H, the sharp C–O band at 1,715 cm^{-1}. Typical absorption bands of PES such as aromatic bands at 725, 870, and 1,578 cm^{-1} from the benzene ring, with one or more substitutes, C–C at 1,412 cm^{-1}, C–SO_2–C at 1,335 cm^{-1}, C–O–C at 1,240 cm^{-1}, S–O band at 1,105 and 1,083 cm^{-1}, respectively [26,27]. The presence of PVP are recognized through the sharp O–H band at 3,430 and 1,715 cm^{-1} corresponding to C=O bond stretching vibration [28]. Fig. 6b shows that no peaks can be found obviously in the clean membrane, indicating the effectiveness of the chemical cleanings.

3.5. Effect of run time

To achieve a stable performance during long-term operation of UF process, it is necessary to clean the fouled membrane and restore the permeation flux of the membrane as much as possible. As we know, the membrane fouling still remains one of the most technical challenges in the separation industries. Membrane fouling leads to the decline of membrane flux, which limits the operation efficiency and increases operation and maintenance costs [29].

The PES composite membrane separation performances and cleaning strategy toward SAOPW were tested using an ultrafiltration test device. Using SAOPW as feed liquids and PES composite membrane were conducted 4 batch time-dependent cycling experiments. After the membrane fouling, the fouled membranes were cleaned with 0.1 M NaOH solution, 0.1 M HCl solution and deionized water in turn. The cleaning cycle of the membrane was determined by recording the change of the membrane flux before and after cleaning under the operating parameters. Fig. 7 presented the flux decline behaviors of PES composite membrane with different filtration cycles under the operating parameters: the temperature 25°C, the operating pressure 0.1 MPa, the oil concentration of feed 100 mg·L^{-1} and the time interval 1 h. Permeate fluxes of membrane were recorded every 15 min to observe the changes of membrane flux. As shown in Fig. 7, membrane permeate flux in each cycle (60 min) is negatively correlated with run time, which decreases with time. After each cycle of the filtration process, the permeation flux of the PES composite membrane after chemical cleaning was basically recovered to the initial flux, although the membrane flux after recovery showed a downward trend. Therefore, a duration of 60 min was chosen as the optimum run time for each cycle.

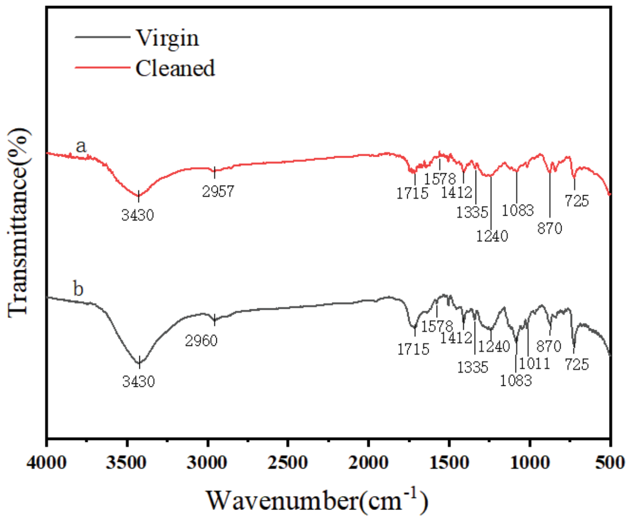

Fig. 6. Fourier-transform infrared spectra of virgin membrane (a), and cleaned membranes (b).

membrane flux recovery ratio (F_r) is an important indicator to evaluate the membrane antifouling performance and the extent of the possible reversible fouling [14]. It is generally believed that the higher the flux recovery ratio, the stronger the antifouling performance of the membrane [30]. The F_r of the polluted membranes for different cycles after cleaning is shown in Fig. 8. It can be seen from Fig. 8 that the values of F_r for the prepared PES composite membrane

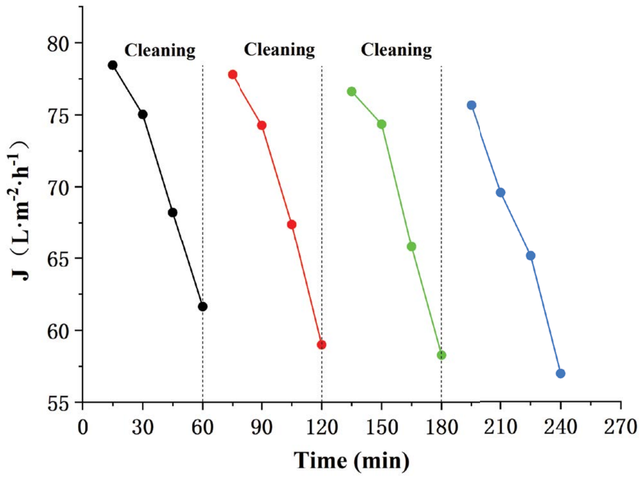

Fig. 7. Flux decline behaviors of polyethersulfone composite membrane with different filtration cycles.

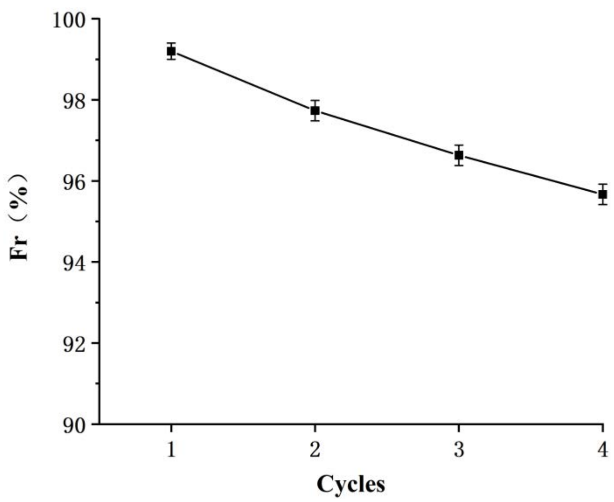

Fig. 8. Membrane flux recovery rate of polyethersulfone composite membranes in SAOPW filtration experiments.

ranged from 95% to 99%, and F_r decreased gradually after each cycle (from 99% to 95%) for PES composite membrane after filtering the SAOPW, which was still higher than other PES membranes from the literatures, with the first F_r values of the PES membranes were lower, <65% and 82.9%, respectively [28,31], indicating that this cleaning strategy is effective and feasible. However, small-sized floc embedded in membrane pores maybe resulted in irreversible membrane fouling of the membrane, which weakens the filtration effect of the membrane and leads to a decrease in the filtration flux [32].

3.6. Analysis of membrane fouling

In general, there are two types of membrane fouling: reversible fouling and irreversible fouling. The membrane fouling that can be physically cleaned is reversible membrane fouling. On the contrary, membrane fouling that cannot be physically removed and accumulates throughout the

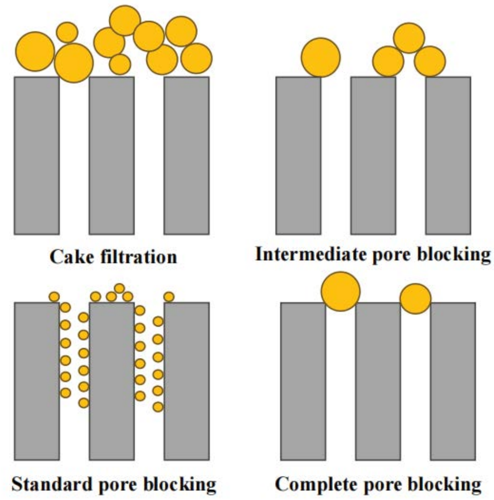

Fig. 9. Four classic fouling models.

entire ultrafiltration process, ultimately requiring chemical cleaning to remove, is called irreversible membrane fouling [33,34].

Four classic fouling models were used to study the fouling mechanism of ultrafiltration membranes [35]. Cake filtration refers to the deposition and accumulation of particles on the membrane surface, forming a cakelike layer; intermediate pore blocking refers to a mix of particles of different sizes cluster at the pore opening; standard pore blocking refers to the smaller particles entering the membrane pores and shrinking the membrane pores, thus reducing the membrane permeability; and complete pore blocking refers to the fact that particles which are larger than the size of pore opening completely block the pore opening (Fig. 9) [35–39].

Fig. 10 shows the correlation between different pore blockage models of ultrafiltration membranes. It can be seen that the cake filtration model and pore blocking model fit well with experimental data. The correlation coefficients and slopes obtained from different pore blocking models are shown in Table 3. It can be seen that correlation coefficient (R^2) values of the complete pore blocking model fits the best, but the values of R^2 for the other three pore blocking models are very close, indicating that both pore blocking and cake filtration contribute to membrane fouling. Therefore, it is preliminarily determined that the membrane fouling in ultrafiltration membrane filtration of emulsified oil wastewater is mainly caused by the complete pore blocking model, but it may also be the result of the combined effect of the four classic fouling models under the experimental conditions mentioned above. The similar results reported by Xing et al. [40], also indicated that that single models did not characterize the membrane fouling mechanism.

3.7. Process economy

The operational costs for the process tested at pilot test were estimated and results summarized in Table 4. The operating cost is mainly composed of four parts: chemical cleaning, electricity, labor service and depreciation and maintenance. Calculation of the operating cost is based on

Table 3
Model parameters obtained for different pore blocking models with ultrafiltration membrane

Models	Correlation coefficient (R^2)	Slope (k)
Cake filtration	0.953	0.000002 s·m^{-2}
Intermediate pore blocking	0.964	0.00008 m^{-1}
Standard pore blocking	0.969	0.0003 s$^{0.5}$·m$^{0.5}$
Complete pore blocking	0.974	0.0055 s^{-1}

Table 4
Operating cost of ultrafiltration process for SAOPW treatment

Description	Cost (USD/m^3)
Chemical cleaning	0.15
Electricity	0.18
Depreciation and maintenance costs	3.15
Labor service cost	0.25
Total costs	3.73

an SAOPW treating capacity of 1 m^3/h. As shown in Table 4, the total operating costs using UF process is about 3.73 \$/m^3, which is lower than that of the traditional oily wastewater treatment varying from 3.65 to 4.5 \$/m^3 of wastewater treated, but slightly higher than the cost of treating cold-rolling emulsion wastewater (3.01 \$/m^3) [3,33,41]. Depreciation and maintenance costs accounted for 84.5% of the total cost of wastewater treatment, which is much higher than that of inorganic ceramic membranes (37.5%) [3]. The cost of UF treatment mainly depends on the material of the membrane and characteristics of oily wastewater. Generally speaking, the capital costs of the ceramic membrane (2,000–4,000 \$/m^2) is significantly higher than polymeric membranes (50–200 \$/m^2) due to the application of expensive inorganic precursors such as zirconia and alumina [4,42,43]. Again, considering the aspect of membrane lifetime, the depreciation and maintenance costs was found to be more competitive to use organic membrane to treat the SAOPW.

Table 5 summarizes some of the main characterizations of modified UF membranes for the treatment of oily wastewater. It can be found that the UF membrane prepared in this study has superior separation performance in treating oily wastewater. It is hypothesized that PES composite UF membranes have a service life of about 5–7 y, which offers an alternative treatment approach that removes oil from water for SAOPW treatment. Despite the successful utilization of UF on the treatment of SAOPW on a laboratory scale, there are still some challenges in realizing these techniques on an industrial scale. Antifouling strategies, stable oil/water emulsions in the feed and operating conditions are required to maintain the successful UF separation performance for potential industrial applications. In addition, changes of feed wastewater quality and the harsh and uncontrollable on-site environment are also an important factor leading to the success of industrial applications [4,11]. Therefore, in order to ensure the stability of the effluent quality and meet the requirements of environmental standards, it is necessary to carry out in-depth treatment after UF.

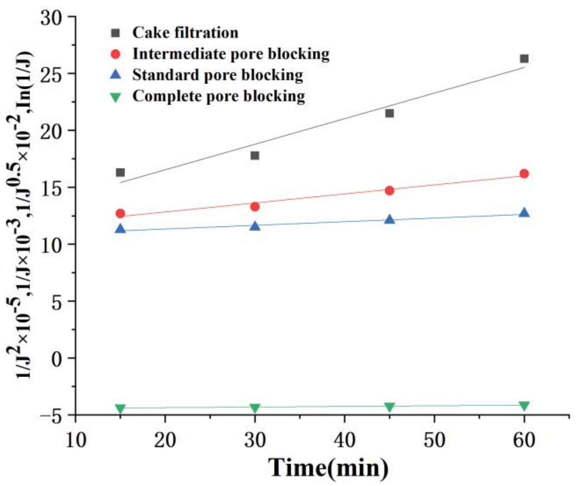

Fig. 10. Plots of flux functions vs. time for four different pore blocking models.

4. Conclusions

In this work, the removal of oil from SAOPW with prepared PES composite UF membranes was performed. The effects of operating parameters were systematically investigated, and the separation performance and economics of the process were evaluated on the experimental test. The findings of this study may be summarized as follows:

- PES composite UF membrane can effectively remove oil in SAOPW, the oil removal rate and water permeation

Table 5
Comparison of separation performance of ultrafiltration membranes for treatment of oily wastewater

Membrane	Flux (L·m^{-2}·h^{-1})	Rejection	Anti-fouling performance (F_r)	References
PSf (MBHBA)	700	90%	45%	[44]
PAN (PAMAM)	420	99%	61%	[45]
PSf (AA)	145.3	–	74.3%	[46]
Polyethersulfone (PEI)	72	–	89.4%	[47]
ZrO_2 (PAA)	63.26	88.91%	69.7%	[48]
Polyethersulfone (PVP)	260.2	91%	90.5%	This work

flux are above 91% and 260 ($L \cdot m^{-2} \cdot h^{-1}$) at 0.1 MPa at room temperature, respectively, which shows superior separation performances in treating SAOPW.

- Four classic fouling models are used to investigate the membrane fouling mechanism, and the results indicate that the experimental data are well described by the complete pore blocking model.
- Total operating cost of the UF process is about 3.73 $/$m^3$ and the COD and oil concentration of the effluent are lower than 45 and 5.0 $mg \cdot L^{-1}$, respectively, which can meet the requirements of the corresponding standard of "China's Comprehensive Wastewater Discharge Standard" (GB8978-96).
- PES composite UF membrane has shown a promising alternative in treating SAOPW, effective research on the development of UF membrane with high flux and high anti-oil-fouling properties, as well as combined techniques with other technology is urgently needed for real-world SAOPW treatment.

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