Journal of Environmental Sciences Vol. 18, No. 6, pp. 1077—1081, 2006

ISSN 1001—0742
CN 11—2629/X

Article ID: 1001-0742(2006)06-1077-05 **CLC number**: X131.2 **Document code**: A

Flux enhancement during ultrafiltration of produced water using turbulence promoter

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Abstract: Concentration polarization and membrane fouling remain one of the major hurdles for the implementation of ultrafiltration of produced water. Although many applications for ultrafiltration were already suggested, only few were implemented on an industrial scale. Among those techniques, turbulence promoter can be more simple and effective in overcoming membrane fouling and enhancing membrane flux. As for the result that turbulence promoter increase fluid velocity, wall shear rates and produce secondary flows or instabilities, the influence of turbulence promoter was investigated on permeate flux during produced water ultrafiltration and the potential application of this arrangement for an industrial development. Experimental investigations were performed on 100 KDa molecular weight cut-off PVDF single-channel tubular membrane module using four kinds of turbulence promoters. It is observed that the significant flux enhancement in the range of 83%—164% was achieved while the hydraulic dissipated power per unit volume of permeate decreased from 31%—42%, which indicated that the using of turbulence promoter is more efficient than operation without the turbulence promoter. The effects of transmembrane pressure and cross-flow velocity with and without turbulence promoter were studied as well. Among the four kinds of turbulence promoters, winding inserts with 20.0 mm pitch and 1.0 mm wire diameter showed better performances than the others did.

Keywords: hydraulic dissipated power; flux enhancement; turbulence promoter; produced water; ultrafiltration

Introduction

The application of ultrafiltration for produced water treatment is still costly in terms of energy consumption and equipment cost compared with conventional water treatment processes. The high-energy consumption comes from the high circulation velocity, and it is necessary for controlling concentration polarization and membrane fouling, which still remain a topical problem for an industrial development of ultrafiltration processes. Membrane fouling in ultrafiltration is complex, accumulation of substances on the membrane surface and/or within the membrane pores which results in deterioration of membrane performance and permeate flux decline with time. Various membrane fouling controlling techniques have been used to enhance membrane flux, such as the applying of additional electric fields and ultrasonic fields (Huotari *et al.*, 1999; Kobayashi *et al.*, 1999), the adoption of rotating membranes (Pharoah *et al.*, 2000), membrane surface modification (Ma *et al.*, 2001; Nabe *et al.*, 1997), rapid backflushing pulsing and shocking (Ma *et al.*, 2001; Srijaroonrat *et al.*, 1999), feed pretreatment (Mietton and Aim, 1992), gas sparging (Cui and Wright, 1994) and other methods.

Except those techniques, turbulence promoter can be more simple and effective in overcoming membrane fouling and enhancing membrane flux. Gupta *et al.* (1995) produced helical baffles by winding wires onto rod supports. These baffles were located axially inside a ceramic tubular membrane and yeast suspensions and oil and water mixtures were filtered. Permeate flux enhancement of up to 50% was observed at the same hydraulic power. Gan and Allen (1999) carried out an experimental study to evaluate flux performance and solid retention efficiency of a ceramic membrane system in the microfiltration of a primary municipal sewage effluent by employing a helically wound baffle installed inside the cross flow channel. The baffles were helically wound and soldered onto a 0.25-mm central wire. A 22% flux improvement was achieved by installing the helical baffle inserts. Yen *et al.* (2000) obtained a considerable improvement in permeate flux during ultrafiltration of Dextran T500 aqueous solution by inserting concentrically a steel rod into tubular module. They observed that the flux improvement can reach 200% but the improved performance based on the same hydraulic dissipated power was about 20%. Xu *et al.* (2002) used turbulence promoters with different configurations in ceramic membrane bioreactor. The results confirmed that the introduction of inserts led to better flux in comparison with empty tube. Winding inserts with 10 mm pitch and 1.6 mm wire diameter showed better performances than the others did. The flux under the same operation parameters increased from 70 to 175 $L/(m^2 \cdot h)$ and the effluent quality would not reduce in comparison with empty tube. Krsti *et al.* (2003) demonstrated that use of a static mixer as turbulence promoter results in enhanced cross-flow microfiltration of skim milk. Experimental investigations were performed on 50 nm and 100 nm ceramic tubular membranes. The use of a static mixer provided a significant reduction of membrane fouling and an increase of more than 700%

Foundation item: The National Basic Research Program (973) of China (No. 2004CB418505); *Corresponding author in permeate flux for both membranes compared with that obtained without a static mixer at the same feed flow rate. The similar flux enhancement indicates that surface layer resistance dominates the overall fouling resistance. Although the power consumption was significantly increased by using a static mixer, a decrease of more than 25% in specific energy consumption for both membranes was achieved with static mixer as compared to arrangement without static mixer in experiments performed at the same cross-flow velocity.

Although the treatment of effluents with turbulence promoters by ultrafiltration has been presented by some researchers, their focus was not on produced water treatment. This project was to investigate whether the use of turbulence promoter could improve the produced water ultrafiltration performance. The efficiency of various turbulence promoters geometries with different pitch were checked from the aspects of flux enhancement and energy consumption under different operation conditions, as these factors could be decisive for a practical application of turbulence promoters in the produced water ultrafiltration.

1 Experimental

1.1 Characteristics of the produced water

The analysis of the produced water used as feed to the ultrafiltration membrane is given in Table 1. It is supplied from the Daqing Oilfield in China. As it can be seen, the produced water is a very complex medium including both dissolved constituents, colloids and large particles.

Table 1 Characteristics of the produced water

Parameters	Produced water	Parameters	Produced water
Oil concentrate, mg/L	12.52—84.42	TDS, mg/L	3100—5800
SS, mg/L	7.89—89.16	COD, mg/L	450.17—1280.55
Median diameter, μm	1.07—7.68	pH value	7.2—8.1
Turbidity, NTU	18.8—97.6	Temp., ℃	35—40

1.2 Ultrafiltration membrane

A 100 KDa MWCO PVDF single-channel tubular membrane module (5-HFM-251-PVI, Koch, USA) was used in this study. The module had the following dimensions: length of 1400 mm, inner diameter of 20.0 mm and surface area of 0.1 m^2.

1.3 Turbulence promoter

Four kinds of turbulence promoters were used. Configurations and parameters of the promoters are shown in Fig.1 with inserts. These inserts were all made of stainless steel. The static turbulence promoter was incorporated into a tubular membrane and was fixed appropriately to avoid any moving due to the fluid flow.

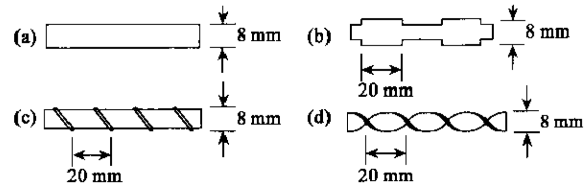

Fig.1 Schematic diagram of insert configurations
a. cylindrical inserts (signed as TP1), rod diameter: 8 mm; b. column cross-section inserts (signed as TP2), rod diameter: 8 mm, length of pitch: 20 mm; c. winding inserts (signed as TP3), rod diameter: 6 mm, length of pitch: 10, 20, 30 and 40 mm, wire diameter: 1 mm; d. helical inserts (signed as TP4), rod diameter: 8 mm, length of pitch: 20 mm

1.4 Experimental apparatus

The experiments were carried out on a crossflow ultrafiltration apparatus as schematically presented in Fig.2, which consisted of a feed reservoir thermostated at (38±1)℃, a feed pump, a filtration unit and measuring equipment (pressure gauge, flow meter). The feed flow rate (Q) was determined with the accuracy of ±2% flow meter. The permeate flux was constantly returned to the feed tank together with the retentate in order to maintain a constant inlet feed concentration. All measurements in this study were carried out five times and the results were averaged. The measurement reproducibility was good; the deviations between parallel experiments were in the range of ±5%.

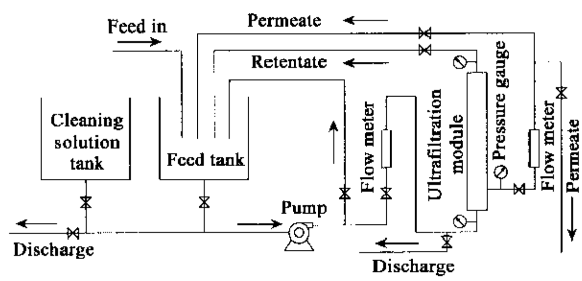

Fig.2 Schematic of the experimental set-up

1.5 Membrane regeneration

Between two runs, the membrane was regenerated by the following route in turns. The tap water was used after each step in order to rush of the residual cleaning agent.

(1) 10 min washing with a 1% sodium dodecylbnzene sulfonate solution at 40℃;

(2) 10 min washing with a 1% sodium hydroxide solution at 40℃;

(3) 10 min washing with a 1% dicarboxyl solution at 40℃.

1.6 Calculations

The efficiency of the static turbulence promoter was checked through determination of flux improvement (FI), the increase of hydraulic dissipated power (PI), and the reduction of specific energy consumption (ER). The calculations were defined as follows:

$$FI = \frac{J_{TP} - J_{NTP}}{J_{NTP}} \times 100 \quad (1)$$

$$PI = \frac{P_{TP} - P_{NTP}}{P_{NTP}} \times 100 \quad (2)$$

$$ER = \frac{E_{NTP} - E_{TP}}{E_{NTP}} \times 100 \quad (3)$$

where, TP represents turbulence promoter and NTP represents empty tube without adopting turbulence promoter.

The hydraulic dissipated power (P, W) (Gupta *et al.*, 1995) can be expressed as a product of feed flow rate (Q, m^3/s) and pressure drop along the module (ΔP, Pa):

$$P = Q \cdot \Delta P \quad (4)$$

W hile the specific energy consumption (E, kWh/m^3) was defined as the hydraulic dissipated power per unit volume of permeate, A is the membrane area (m^2) and J is the permeate flux (m/s):

$$E = \frac{P}{3.6 \times 10^6 \cdot J \cdot A} \quad (5)$$

2 Results and discussion

2.1 Effect of the different turbulence promoters

2.1.1 Effect of inserts configurations on permeate flux

The variations of permeate flux during operation obtained with four kinds of turbulence promoters (TP mode) and without a turbulence promoter (NTP mode) are shown in Fig.3. The experiments were carried out at the same feed flow rate of 1.80 m^3/h and the same transmembrane pressure (TMP) of 0.35 MPa. Each experiment was carried out for 6 h respectively.

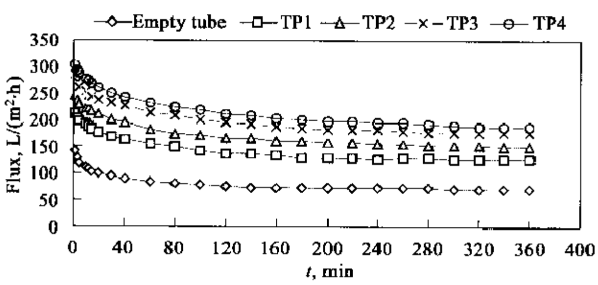

Fig.3 Effect of inserts configurations on flux
Conditions: Q=1.80 m^3/h; T=38℃; TMP=0.35 MPa

Fig.3 shows that the four TP modes have the similar flux behaviors against time. The flux of empty tube declined very fast at the beginning of filtration, then the permeate flux can retain steady for a long time. But the insertion of the turbulence promoter caused a large improvement of the permeate flux and the helical inserts can cause the largest improvement among the four kinds of turbulence promoters, the flux curve of the mode of TP declined evenly with time against that of NTP. This can be explained by the characteristic flow field created by using the turbulence promoter. Beside the helical component of the flow, which enhances radial mixing and creation of secondary flows, left and right-hand alternations of helices cause a creation of vortex which additionally increases the shear rate at the membrane surface leading to scouring of the membrane surface more than in the case of the empty tube. The enhanced scouring in the TP mode of operation remove particles from the surface and reduces the thickness of the micellar deposit on the membrane surface, made the concentration can not remain steadily, which leading to a large improvement of the permeate flux.

2.1.2 Energy consumption of different insert configurations

The comparison of process performances during the operation in NTP and TP modes at the same feed flow rate and the same TMP are shown in Table 2. The values of average permeate flux at a 360-min filtration time showed that the TP1, TP2, TP3 and TP4 were 141.6, 163.6, 184.6 and 200.5 L/(m^2·h). The permeate flux with inserts, irrespective of their configurations, was higher than the empty tube. On the other hand, the hydraulic dissipated power (P) or power required for circulating the fluid increases because of the increase in pressure drop along the module leading to a large energy consumption. However, in spite of that power enlargement, the reduction of the specific energy consumption of more than 33%, 31%, 42% and 38% was achieved with TP1, TP2, TP3 and TP4. For the same flow rate and TMP, TP3 showed better performance than the others did. Therefore, the TP3 has the greater values in actual application.

Table 2 Energy consumption of different insert configurations[a]

Parameter	TP1	TP2	TP3	TP4	Empty tube
Average flux[b], L/(m^2·h)	141.6	163.6	184.6	200.5	77.4
Axial pressure drop, MPa	0.016	0.019	0.018	0.021	0.013
P, W	8.00	9.50	9.00	10.50	6.50
E, kWh/m^3	0.56	0.58	0.49	0.52	0.84
FI, %	83	111	139	159	
PI, %	23	46	38	62	
ER, %	33	31	42	38	

Notes: [a] Configurations and parameters of the promoters were in Fig.1; [b] the average of the flux in 0—360 min; Q=1.80 m^3/h; T=38℃; TMP=0.35 MPa

2.2 Effect of winding inserts with different pitches on permeate flux

As for the TP3 (winding inserts), the different pitches can also have different effect. Fig.4 is the effect of winding inserts on cross-flow ultrafiltration with different pitches. The corresponding values of energy consumption are shown in Table 3.

The pitch was an important parameter of the winding inserts. The permeate flux increased with the

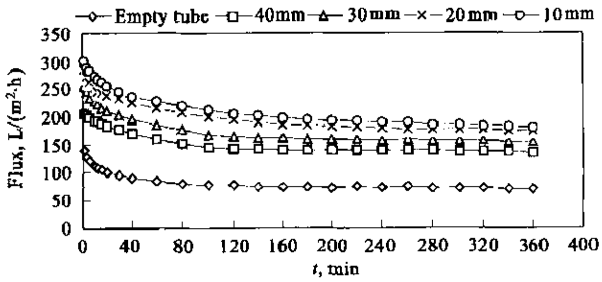

Fig.4 Effect of winding inserts with different pitches on flux
Conditions: Q=1.80 m^3/h; T=38℃; TMP=0.35 MPa

pitches decrease. The TP3-10 has the largest flux enhancement while the TP3-40 has the least, which can be seen by comparing with Table 3. The average flux during the filtration period were 204.3, 184.6, 160.6 and 152.5 L/(m^2·h) and the specific energy consumption were 0.51, 0.49,0.53 and 0.56 kWh/m^3 for the 10, 20, 30 and 40 mm pitches. The corresponding reduction of specific energy consumption were 39%, 42%, 37% and 34%, respectively. For the same flow rate and TMP, the TP3-20 showed a better performance than the others did in the reduction of specific energy consumption. The value of permeate flux of 10 mm pitch was higher than the others but the energy consumption also higher than others because of larger axial pressure drop as the results of a smaller pitch. Moreover, if the pitch was too small it would be difficult for manufacturing. So the appropriate pitch of the winding inserts was 20 mm in this study.

Table 3 Energy consumption of different pitches

Parameter	TP3-10 (10 mm)	TP3-20 (20 mm)	TP3-30 (30 mm)	TP3-40 (40 mm)	Empty tube
Average flux^a, L/(m^2·h)	204.3	184.6	160.6	152.5	77.4
Axial pressure drop, MPa	0.021	0.018	0.017	0.017	0.013
P, W	10.50	9.00	8.50	8.50	6.50
E, kWh/m^3	0.51	0.49	0.53	0.56	0.84
FI, %	164	139	107	97	
PI, %	62	38	31	31	
ER, %	39	42	37	34	

Nores: ^{a} The average of the flux in 0--360 min; Q=1.80 m^3/h; T=38℃; TMP=0.35 MPa

2.3 Effect of TMP on permeate flux

In Fig.5, the steady state permeate flux (filtration at 180 min) is plotted against TMP for TP3-20 and NTP studied. The experiments were carried out at the feed flow rate of 1.80 m^3/h and at 38℃. For NTP mode of operation, the increase of TMP led to increase of the permeate flux at lower TMP. But with the TMP increased, the permeate flux increased slowly and reached the limiting value at 0.40 MPa, then the decrease of permeate flux at higher TMPs was observed for NTP mode. It can be inferred that the concentration polarization around the membrane surface is serious at the time. But for TP mode of operation, significant flux improvement was obtained and no limiting permeate flux at all examined TMPs. The main reason is that the turbulence promoter can stir the fluid and form secondary flows to enhance mass transfer and mixing fluid around the membrane surface, which decreased the fouling martial deposition on the surface. So the permeate flux increased in direct proportion to TMP for TP mode, which have almost the similar flux behaviors to pure water ultrafiltration. This indicated turbulence promoter could enlarger the TMP operation scope.

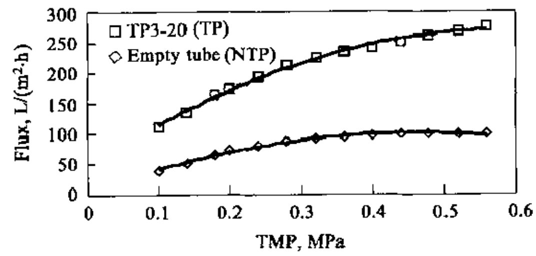

Fig.5 Permeate flux vs. TMP for NTP and TP modes of operation
Conditions: Q = 1.80 m^3/h; T = 38℃

2.4 Effect of feed velocity on permeate flux

Fig.6 shows the permeate flux variations with feed velocity for NTP and TP modes of operation. The experiments were carried out at the TMP of 0.35 MPa and at 38℃. Both of modes showed similar flux variations with the feed velocity. But with the increasing of feed velocity, the flux difference between TP and NTP come to little. As a result of the flow rate increased, the liquid shear rate in the vicinity of the membrane surface increased and enhanced the membrane mass transfer coefficient, which weaken the function of turbulence promoter but enhanced the empty tube flux. The results show that the introduction of turbulence promoter at low flow rates can attain the same permeate flux compared with the empty tube at high flow rates. It is not prominent for the introduction of turbulence promoter at high-recirculated feed velocity. Moreover, the energy consumption can be save under low recirculated flow rate (<2 m/s).

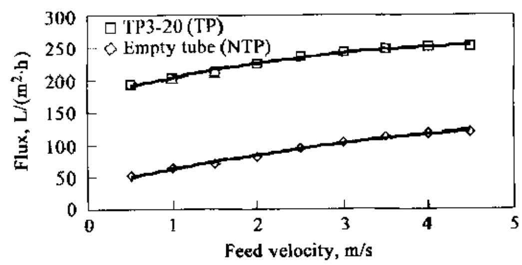

Fig.6 Permeate flux vs. feed velocity for NTP and TP modes of operation
Conditions: Q=1.80 m^3/h; T=38℃

3 Conclusions

The effect of different turbulence promoter geometries and shape has been explored and the optimum operating conditions were identified. The experimental results clearly show that the improved performance of produced water cross-flow ultrafiltration can be obtained by using the turbulence promoter. The insertion of turbulence promoter caused a large improvement of the permeate flux and the winding inserts with 20 mm ditches can cause the largest improvement of the permeate flux with the least energy consumption among the four kinds of turbulence promoters. Compared to the operation without turbulence promoter, the average flux improvement during the filtration period ranged from 83% to 164% and the specific energy consumption reduction ranged from 31% to 42%. The use of the turbulence promoter at very low-recirculated feed velocity of 1—2 m/s and optimum TMP of 0.30—0.35 MPa can provide the commercially acceptable values for filtration.

Acknowledgements: The authors wish to acknowledge the kind support of Mr. Ban Hui and Miao Bao-lin at the 2th Production Factory of Daqing Oilfield.

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(Received for review November 21, 2005. Accepted February 13, 2006)