DESALINATION

Desalination 221 (2008) 370–375

www.elsevier.com/locate/desal

An empirical model for membrane flux prediction in ultrafiltration of surface water

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Received 16 September 2006; accepted 3 January 2007

Abstract

Surface water was purified by ultrafiltration membrane to produce drinking water. The membrane flux decreases with increasing turbidity and there is a somehow linear relationship between membrane flux and the log of turbidity. Mathematical model was built to predict the membrane flux based on this. The parameters which concerned the model were raw water quality (turbidity), transmembrane pressure (ΔP) and temperature. The result showed that the model can well predict the membrane flux.

Keywords: Ultrafiltration; Drinking water production; Membrane flux; Model

1. Introduction

Water resource degradation coupled with more stringent water quality regulations have promoted an increasing use of low-pressure membrane processes: microfiltration (MF) and ultrafiltration (UF). The price of membrane filtration has also fallen extensively in recent years. Membrane techniques are much efficient principally with the removal of natural organic compounds (humic substances), bacteria, parasites and their end spores, and they reduce the necessity of carrying out water disinfection after the treatment process [1].

With UF systems, the quality of the produced water (in terms of particles, bacteria and viruses) is constant and independent on operating conditions and on the raw water quality. On the contrary the plant productivity depends on these parameters which influence membrane flux. Most of the research activities in this field now focus on different ways to enhance plant's productivity. But advanced control strategies require models describing the influence of operating parameters, in order to perform short- or long-term predictions of the plant behavior [2]. Development of these models requires a better knowledge of the influence of operating parameters on productivity, which lies in a better understanding of fouling during UF of raw water. It seems now necessary

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Presented at the conference on Desalination and the Environment. Sponsored by the European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort, Halkidiki, Greece, April 22–25, 2007.

doi:10.1016/j.desal.0000.00.000

to be able to operate industrial plants taking into account the influence of raw water quality on membrane flux, with the aim to further enhance the plant productivity [3].

Prediction of flux decline for UF and generally all membrane applications is very important both for the assessments of overall productivity, optimization, automation and for scaling up these system. Objective of this research was to develop a simple model to characterize flux under specific operation conditions. The characteristic model parameters included raw water quality (water turbidity), temperature and transmembrane pressure. The model was tested using data from a pilot scale UF system.

2. Experimental

2.1. Raw water characteristics and membrane characteristics

Songhuajiang river water was used as raw water and the qualities of raw water are given in Table 1. The membranes used in this study were UF membrane. UF membranes made of PVC were used in the experiments. The nominal molecular weight cut off of these membranes as reported by the manufacture is 80,000 Dalton. Characteristics of the membranes are shown in Table 2.

2.2. The process

Fig. 1 shows the schematic diagram of the UF facility used for the treatment of Songhuajiang river water. Two pumps are used for feed and backwash, respectively. River water was pumped into the raw water tank for UF. Cross flow filtration inside the hollow fiber module divides feed into permeate and retentive which were recycled to the raw water tank. Backwashing was performed by pumping the permeated water from the storage tank to the shell side of the hollow fiber membranes in the module. After washing the fouling from the membrane, the water was discharged from the recirculation loop.

The apparatus was constructed in Harbin Water Treatment Plant. Fig. 2 shows the photo of this 120 m^3/d pilot plant.

Temperature corrections to 20°C for the recorded membrane flux were made according to

$$J = \frac{Q_{\text{perm}} \exp\left[-0.0239 \cdot (T - 20)\right]}{A} \tag{1}$$

Table 1
Characteristics of raw water

Parameter	Range	Average
Temperature (°C)	1–29	8.3
Turbidity NTU	6.3–570	21
pH	6.4–7.9	7.4
COD$_{\text{Mn}}$ (mg/L)	2.4–8.2	4.9

Table 2
Membrane characteristics data

Parameter	UF membranes
Type	Hollow fiber
Material	PVC
Molecular weight cut off (Da)	80,000
Hollow fiber internal diameter (mm)	0.9
Hollow fiber external diameter (mm)	1.5
Length (mm)	1400
Membrane surface area (m^2)	48
pH range of operation	21–3
Temperature range (°C)	0–40

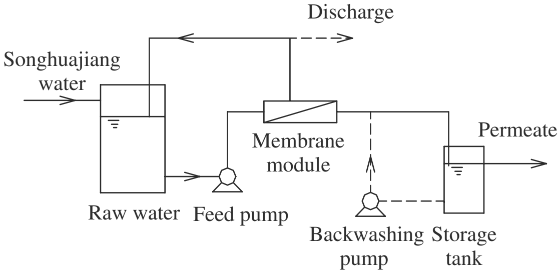

Fig.1. Schematic flow diagram of the experiment.

Fig. 2. Photo of the 120 m^3/d pilot plant.

It is based on the variation of water viscosity with temperature, where Q_{perm} is the permeate flow rate, T is the temperature (°C), A is the surface area of membrane, m^2 and J is the corrected permeate flux.

3. Mathematical modeling

A model presented by Jones et al. [4] is used as a foundation for the development of the model used in this study. The modeling of filtration yield can be also based on the analysis of resistances [5,6] encountered by the liquid passing through the membrane, and by allowing for the phenomena affected by mutual interaction: membrane-substances present in natural waters. Although the aforementioned model was only tested in the constant pressure mode, using relatively low fouling source waters, the core of the model was not limited to these conditions. In the proposed membrane filtration model of natural waters, the change (increase) of resistance in particular cycles is connected with membrane blocking, referred to as fouling, which is a series of physical, chemical and biological phenomena, resulting in pollution of reversible or irreversible character. This hydraulic resistance can be found using the well-known resistance in series model, which relates the flux through the membrane (J) to the applied transmembrane pressure (ΔP).

$$J = \frac{\Delta P}{\mu \cdot (R_m + R_c + R_i)} = \frac{\Delta P}{\mu \cdot R_t} \tag{2}$$

Here μ is the viscosity of the fluid being filtered and the R terms represent the intrinsic membrane resistance (R_m), the reversible hydraulic resistance, commonly caused by a cake layer or concentration polarization (R_c), the irreversible hydraulic resistance (R_i), and the total hydraulic resistance (R_t).

In our previous work [7] we identified that there is a straightforward relationship between permeate flux and log (turbidity) for surface water. The different slopes of the two straight lines are related to different specific resistance due to fouling. In this work we also get the results. The effects of raw water quality of Songhuajiang river water on UF behavior for the PVC membranes are shown in Fig. 3 where the measured fluxes are plotted against the turbidities in raw water. It is apparent that the flux decreases with increasing turbidity in accordance with a linear relationship between the flux and log (turbidity).

Now we can draw a conclusion that when the transmembrane pressure is constant, there is a straightforward relationship between permeate flux and log (turbidity). The membrane flux (J) may be defined as

$$J = a \ln Y + b \tag{3}$$

where a and b are constants when the ΔP is fixed, Y is raw water turbidity. In fact the value

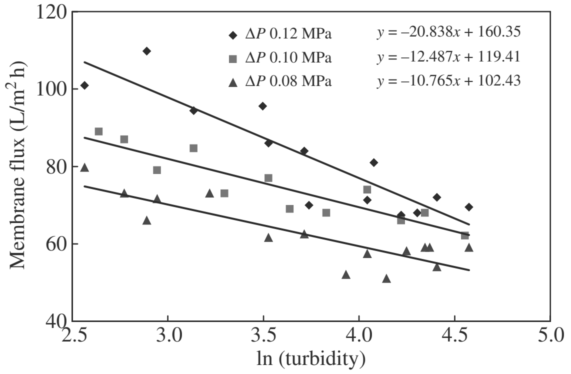

Fig. 3. Effect of feed water turbidity on membrane permeate flux.

of a and b will change along with ΔP variety, which can be seen from Fig. 3: the slope and intercept of the two lines are different. So a and b are the function of transmembrane pressure (ΔP). We can define $a = f(\Delta P)$, $b = g(\Delta P)$, if we further substitute those into Eq. (3), we obtain an expression J in term of ΔP:

$$J = f(\Delta P)\ln Y + g(\Delta P) \tag{4}$$

In the Eq. (2), when the raw water quality is constant, there is a straightforward relationship between permeate flux and transmembrane pressure. Seeing through the form of Eq. (2) We defined

$$\begin{aligned} f(\Delta P) &= \frac{m}{\mu}\Delta P + n \\ g(\Delta P) &= \frac{r}{\mu}\Delta P + s \end{aligned} \tag{5}$$

In Eq. (5), m, n, r, s are constants. Because Eq. (4) has take into account the raw water quality affecting the membrane flux, the Eq. (5) abnegate the R in series. We substitute Eq. (5) into Eq. (4). Therefore, Eq. (4) can be expressed as

$$\begin{aligned} J &= f(\Delta P)\ln Y + g(\Delta P) \\ &= \left(\frac{m}{\mu}\Delta P + n\right)\ln Y + \frac{r}{\mu}\Delta P + s \\ &= \frac{m}{\mu}\Delta P \ln Y + n\ln Y + \frac{r}{\mu}\Delta P + s \end{aligned} \tag{6}$$

We can figure out the model with the help of trend line in Fig. 3. The model was explained in Table 3.

We can get that $m/\mu = -251.62$, $n = 10.468$, $r/\mu = 1448$, $s = -17.403$. When it is 20°C, the viscosity of water is $\mu = 10.02 \times 10^{-4}$ N s/m², it can be figured out that $m = -0.252$, $r = 1.45$, we substitute those into Eq. (6):

$$\begin{aligned} J &= -0.252 \times \frac{\Delta P \ln Y}{\mu} + 10.5 \times \ln Y \\ &\quad + 1.45 \times \frac{\Delta P}{\mu} - 17.4 \end{aligned} \tag{7}$$

Eq. (7) is the model for membrane flux prediction for different transmembrane pressure and raw water quality.

4. Model applications and discussions

Eq. (7) is an empirical model for membrane flux prediction. Fig. 4 showed the membrane

Table 3
Parameter calculation

ΔP (MPa)	Equation	$\frac{m}{\mu}\Delta P + n$	$\frac{r}{\mu}\Delta P + s$
0.12	$J = -20.8 \ln Y + 145.35$	−20.83	160.3
0.10	$J = -15.7 \ln Y + 118$	−12.48	119.4
0.08	$J = -10.7 \ln Y + 92.4$	−10.76	102.4

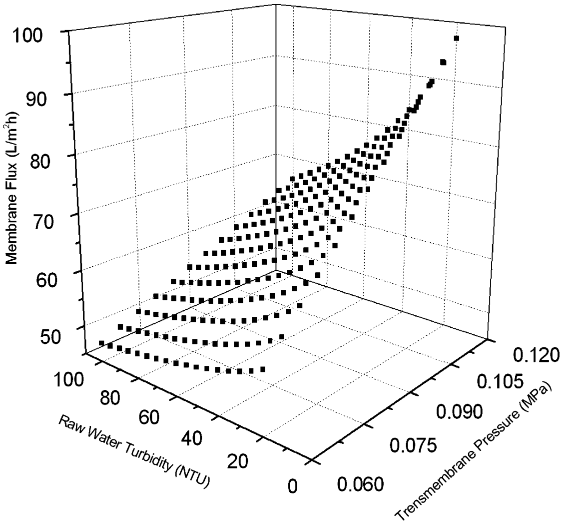

Fig. 4. Prediction of membrane flux with different raw water quality and pressure.

flux prediction by calculating the membrane flux with Eq. (7). We can see from Fig. 4, the more the transmembrane pressure, the more the membrane flux, and the lower the raw water turbidity, the more the membrane flux.

Eq. (7) was developed from Fig. 3, and the temperature was corrected to 20°C. If we take the temperature effect into account, the expression will come to be

$$J(\Delta P,Y,T) = -251\times\frac{\Delta P\ln Y}{\exp\left[0.0239\times(20-T)\right]} + 10.5\times\ln Y + 1448 \times\frac{\Delta P}{\exp\left[0.0239\times(20-T)\right]} - 17.4 \tag{8}$$

Eq. (8) was the mathematical model for different temperature, raw water turbidity and ΔP. We compared the ΔP of 0.11 MPa and 0.09 MPa to validate the model with different transmembrane pressure and different temperature. The results are shown in Table 4.

The correlation coefficient R^2 of $J(\Delta P,T,Y)$ and J is 0.83, which can satisfy the requirement basically. In the mathematical form of the model, the mathematical expression accord with the phenomena in the experiments: the membrane flux has direct proportion to transmembrane

Table 4
Comparison of prediction of the model and actual flux

ΔP (MPa)	Y (NTU)	T (°C)	J predicted (L/m^2 h)	J measured (L/m^2 h)
0.11	53	17	70	74
0.11	47	17.9	73	83
0.11	45	11.6	66	73
0.11	41	19.5	77	87
0.11	23	11.2	74	78
0.11	29	23	89	93
0.11	24	14.3	78	78
0.11	28	23	89	84
0.09	25	6.5	58	62
0.09	64	23	65	64
0.09	57	16.8	61	54
0.09	55	7.4	54	59
0.09	83	23	61	64
0.09	107	23.5	58	59
0.09	95	14	54	61
0.09	26	10.7	62	69
0.09	64	24	66	69

pressure and has inverse proportion to raw water turbidity.

There may be some limitations in the mathematic model. Although we have take into account the influence of membrane resistance in Eq. (4), we do only consider the effect of raw water turbidity. The raw water turbidity may principally affect the resistance of R_c which we think can be removed by backwashing of membrane. Unfortunately the R_i in Eq. (2) does not come to our option. Because there may be an increase in the irreversible resistance, the Eq. (8) cannot predict the membrane flux with membrane UF for a long time. Another limitation is that we think the temperature only affecting the viscosity to simple the model, but it should be the mathematical integral of the all factors that affect the membrane flux.

5. Conclusion

There is a straightforward relationship between permeate flux and log (turbidity) for surface water.

An empirical model was constructed to predict the membrane flux for Songhuajiang river water:

$$\begin{aligned} J(\Delta P,Y,T) = &-251 \times \frac{\Delta P \ln Y}{\exp\left[0.0239 \times (20 - T)\right]} \\ &+ 10.5 \times \ln Y + 1448 \qquad (9) \\ &\times \frac{\Delta P}{\exp\left[0.0239 \times (20 - T)\right]} - 17.4 \end{aligned}$$

Results showed that the model can satisfy the requirement basically.

Acknowledgements

This work was supported by Science and Technology Commission of Shanghai Municipality, Contract No. 052312008. This work was also supported by National Key Technologies R&D Program: 2006BAJ08B06 and 2006BAJ08B02.

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