

The effect of shear rate on controlling the concentration polarization and membrane fouling

R. Bian^a, K. Yamamoto^a, Y. Watanabe^{b*}

^a*Product Development Department, Environmental System Division, Shinko Pantec Co. Ltd.,
Kokusai-Hamamatsucho Bldg., 9-18, 1-Chome, Kaigan, Minato-Ku, Tokyo 105-0022, Japan
Tel. +81 (3) 3459-5941; Fax +81 (3) 3437-3256; e-mail: r.bian@pantec.co.jp*

^b*Department of Environmental Engineering, Hokkaido University, Kita 13, Nishi 8, Sapporo 060-8628, Japan
Tel. +81 (11) 706-6275; Fax +81 (11) 706-7890; e-mail: yoshiw@eng.hokudai.ac.jp*

Abstract

This paper deals with the results from experiments concerning the effects of an increasing shear rate at the edge of the membrane on reducing concentration polarization and on controlling membrane fouling during filtration of river water. Concentration polarization of humic substances in NF and MF membranes can be reduced by increasing the shear rate. The concentration polarization model can predict the removal efficiency of humic substances successfully. The high removal efficiency of humic substances in NF membrane filtration processes can be sustained even when the water recovery rate reaches to 96%, if the membranes are vibrated with the maximum vibratory amplitude of 1". A cake layer formation on the NF membrane surface due to deposition of suspended colloids and humic substances dominates NF membrane fouling. NF membrane fouling can be evaluated by the cake filtration model and controlled by increasing the shear rate. Humic substances with molecular weight of more than 6,000 Da are transported away from the membrane surface by the shear-induced diffusion. Humic substances with molecular weight of 2,000 Da and with molecular weight of less than 500 Da are transported away from the membrane surface not only by the shear-induced diffusion, but also by Brownian diffusion.

Keywords: Nanofiltration; Shear rate; Concentration polarization; Membrane fouling

1. Introduction

Membrane processes are becoming increasingly attractive as an alternative to conventional water and wastewater treatment. A major

obstacle in applying membrane processes for potable water supplies and wastewater treatment is the permeate flux decline due to membrane fouling. This is a problem because the capital and operational costs of membrane systems are directly dependent on the membrane permeate flux. Raw waters contain a wide distribution of

*Corresponding author.

particle size. The membrane fouling mechanisms by small molecular substances, macromolecules and colloids are all different. The small molecular substances can pass through the membrane and become absorbed inside the membrane pores. Macromolecules and colloids are rejected on the membrane surface and tend to form a cake layer. Authors [1] report that for river water filtration the cake formation on the membrane surface results in more serious UF membrane fouling than the absorption of small substances inside the membrane pores.

The removal of dissolved materials such as humic substances in membrane processes is also important when selecting the membrane. During membrane filtration, materials dissolved in the feed water are convectively driven to the membrane surface where they build up a concentration polarization boundary layer near the membrane surface. The formation of concentration polarization boundary layer results in increasing concentration of dissolved materials near the membrane surface; as a result, the removal of dissolved materials declines with time.

The formation of a cake layer on the membrane surface and concentration polarization boundary layer near the membrane surface depend on the back diffusion phenomenon during the filtration process. The back transport mechanisms of small molecular substances, macromolecules and colloids are all different [2]. Large particles are preferentially back-transported by shear-induced diffusion, whereas small materials are transported from the membrane by Brownian diffusion. The back transport mechanisms also depend on the shear rate at the membrane surface.

To control the concentration polarization and membrane fouling, several practical approaches such as modifying the surface chemistry of membrane have been pursued. This study focuses on increasing the back-transport of particles away from the membrane by increasing the shear rate

to counteract the problems. The effects of the shear rate on improving removal of humic substances and controlling membrane fouling are discussed in this paper.

2. Experimental methods

2.1. Source water

Chitose River water was used as experimental raw water. The concentration of humic substances and small colloids in this water is relatively high. The annual average water qualities are: dissolved organic carbon (DOC) = 3.1 mg/L, UV absorbance at 260 nm (E_{260}) = 0.12 cm^{-1} , and turbidity = 25 NTU. After the river water was filtered through 0.45 μm membrane filters, DOC and E_{260} were measured by a Shimadzu, Model TOC-5000, and by a Hitachi U-2000 spectrophotometer with a 1-cm cell at 260 nm, respectively. Fig. 1 shows the correlation between DOC concentration and E_{260} of Chitose River water during the period of October 1994, to December 1999. A good linear relationship, about 32, can be seen between DOC and E_{260} . These results indicate that humic substances are the major components of the natural organic matters in Chitose River water [3].

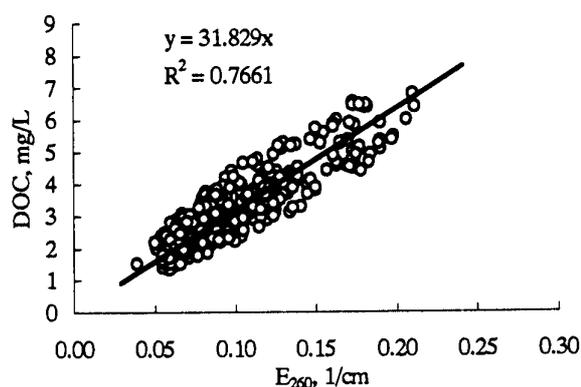


Fig. 1. Correlation between DOC and E_{260} of Chitose River water during October 1994–December 1999.

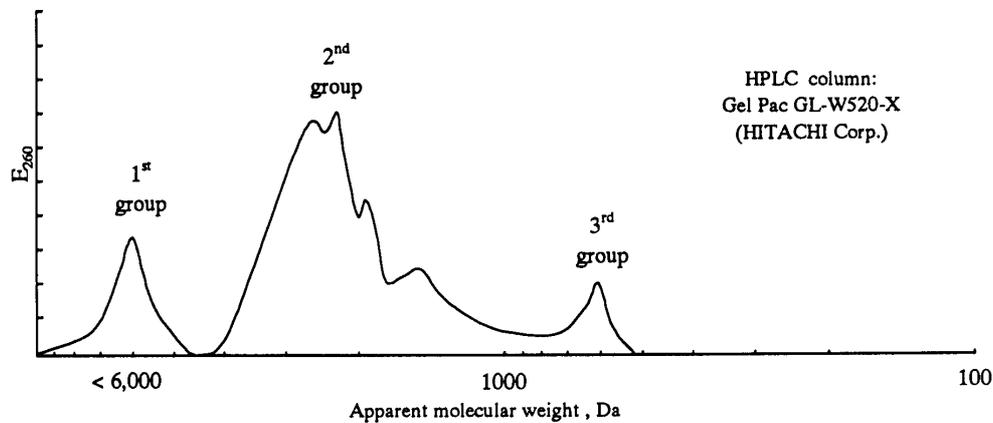


Fig. 2. Apparent molecular weight distribution of humic substances in Chitose River water.

HPLC was used to determine the apparent molecular weight distribution (AMWD) of humic substances in Chitose River water. A Hitachi gel park column and a commercial UV spectrophotometric detector were used. The humic substances in Chitose River water can be divided into three groups by HPLC, as shown in Fig. 2. The apparent molecular weight of the first, second, and third groups are more than 6,000Da, approximately 2,000Da, and less than 500Da, respectively. The first, second, and third groups, respectively, occupy 30%, 60%, and 10% of the total humic substances.

2.2. Experiments of vibratory shear enhanced process

A vibratory shear enhanced process (VSEP [4]) was used for the membrane process to treat the Chitose River water directly without any pre-treatment. The schematic flow diagram of VSEP system is shown in Fig. 3. The VSEP apparatus is composed of four main components, i.e., a driving system that generates vibration, a membrane module, a torsion spring which transfers vibration to the membrane module, and a system for controlling vibration. It can vibrate

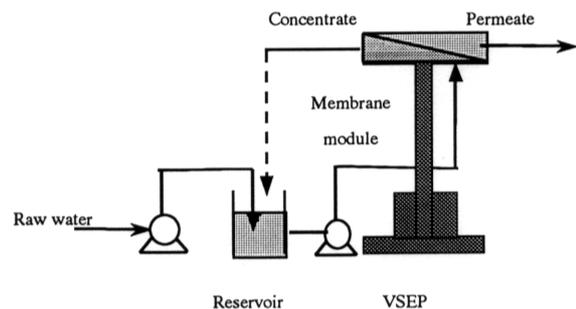


Fig. 3. Schematic flow diagram for the VSEP system.

the membrane with a frequency of 60Hz and maximum vibratory amplitude of 1". A NF membrane (NTR7450) made of sulfonated polyethersulfone with 50% rejection of NaCl and an MF membrane made of Teflon with nominal pore size of 0.45 μm were used.

The shear rate (γ , s^{-1}) at the membrane surface can be calculated by Eq. (1):

$$\gamma = \frac{\text{velocity scale}}{\text{length scale}} \quad (1)$$

Thus the shear rate at the membrane surface set on the VSEP can be calculated by Eq. (2):

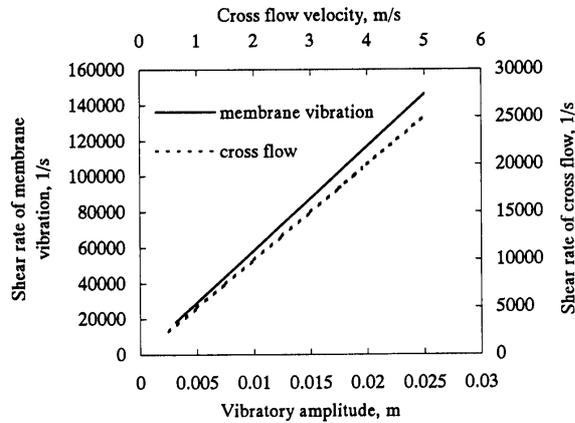


Fig. 4. Comparison between shear rate of cross flow filtration and of membrane vibration when using VSEP.

$$\gamma = \frac{4\pi f^{1.5} \rho^{0.5}}{\mu^{0.5}} P \quad (2)$$

where f is the frequency of vibration (Hz), ρ is the density of solution (water, units: kg/m^3), μ is viscosity of solution (water, units: Pa s) and P is the vibratory amplitude (m) [5]. Fig. 4 shows a comparison between the shear rate of cross flow filtration and of membrane vibration when using VSEP. It shows that the VSEP generates a shear rate of about $120,000 \text{ s}^{-1}$ on the membrane surface at the maximum vibratory amplitude; this is 20 times greater than the shear rate obtained by cross flow filtration with fluid velocity of 1 m/s.

A flat MF and NF membranes with an area of 0.045 m^2 were mounted on the membrane module of the VSEP. The vibratory amplitude at the rim of the membrane module was set at 0, 1/4, 1/2, and 1" to evaluate the effect of vibration. The VSEP membrane apparatus was operated under a constant transmembrane pressure of about 850 kPa for NF and 60 kPa for MF. The permeate flow rate, transmembrane pressure and temperature of the feed water were measured every minute. The VSEP membrane apparatus was operated for about 100h without any hydraulic or chemical cleaning.

3. The effect of shear rate on reducing concentration polarization

3.1. Concentration polarization and removal of humic substances

In membrane filtration processes, some of the components in the solution are rejected by the membrane and accumulate near the membrane surface. Before reaching a steady state the convective flow of the components to the membrane surface is larger than that due to diffusion back-flow to the bulk solution. This phenomenon is called concentration polarization. It is often a serious problem in membrane operations due to its negative influence on the removal of the components and on the permeate flux [6]. As shown in Fig. 5, at the steady state the convective components movement to the membrane surface is equal to the permeate flow and the diffusive back transport of components into the bulk solution.

$$J(C - C_p) = -\frac{dC}{dx} \quad (3)$$

where J is the permeate flux (m/s), C is the components concentration in the bulk solution (mol/m^3), C_p is the concentration in the permeate (mol/m^3), D is the diffusion coefficient (m^2/s), and x is the distance from the membrane surface (m). The diffusion coefficient is assumed to be a constant, so that the following well-known equation can be obtained:

$$J = \frac{D}{\delta} \ln\left(\frac{C_m - C_p}{C_b - C_p}\right) = k \ln\left(\frac{C_m - C_p}{C_b - C_p}\right) \quad (4)$$

where δ is the thickness of the boundary layer (m), k is the mass transfer coefficient, and C_m and C_b are the concentrations at the membrane surface on the feed side and in the bulk solution, respectively. The mass transfer coefficient depends on the molecular weight of the

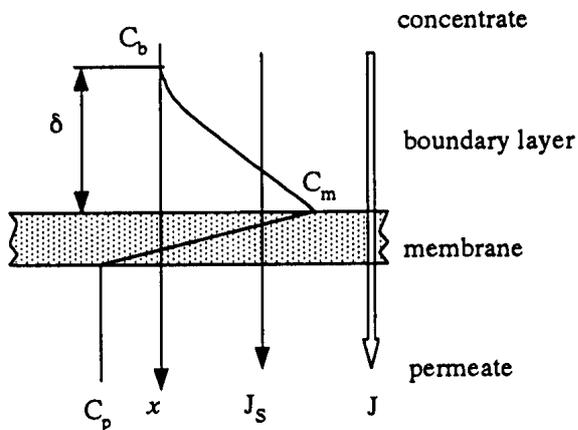


Fig. 5. Concentration polarization.

components and on the shear rate. It can be determined by experiment with different fluid velocities of the tangential flow over the membrane surface. Then the concentration of components on the membrane surface can be calculated from Eq. (4).

There are three ways to evaluate the removal of humic substances in membrane filtration: true removal efficiency based on the concentration of humic substances on the membrane surface, observable removal efficiency based on the concentration in the feed water and removal efficiency based on the concentration in raw water. In this paper the true removal efficiency and observable removal efficiency are used to discuss the concentration polarization, the removal efficiency based on the concentration of humic substances in raw water (hereafter referred to as removal efficiency) is used to evaluate the performance of membrane filtration for water treatment.

3.2. Reduction of concentration polarization of humic substances in NF membrane filtration

It has been considered that concentration polarization arises because of the convective transport of solute to the membrane surface. It is

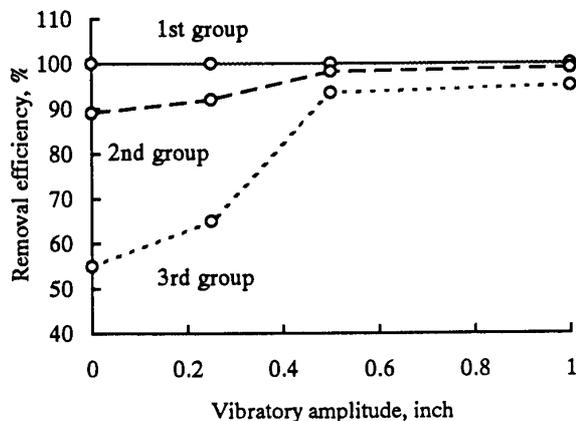


Fig. 6. Relationship between the removal efficiency of humic substances in the NF membrane and the vibratory amplitude.

therefore important to increase the back transport of solute to the bulk solution in order to be able to decrease the accumulation at the membrane surface. This can be achieved by increasing the shear rate. The usual way of increasing the shear rate is to make the feed solution flow tangentially over the membrane surface [6]. In this study experiments for evaluating the effect of vibration on inducing concentration polarization of humic substances in NF membrane filtration were carried out. The NF membrane set on the VSEP was vibrated with a frequency of 60Hz and a vibratory amplitude of 0, 1/4, 1/2, and 1". In these experiments permeate of NF membrane was returned to the reservoir. The areas of chromatographs of raw water and permeate by HPLC were used to evaluate the removal efficiency of humic substances in each group. Fig. 6 shows the relationship between the removal efficiency of humic substances and the vibratory amplitude of VSEP. It shows that the first group can be removed completely by the NF membrane filtration and that the removal efficiency is independent of the vibratory amplitude. This result shows that the molecular size of humic substances in the first group is larger than the NF membrane pore size. The removal efficiencies of

humic substances in the second and the third groups increases with increasing vibratory amplitude of VSEP.

Eq. (4) can be rewritten to show the relationship between observable removal efficiency, true removal efficiency and shear rate as the following Eq. (5):

$$\ln \frac{1 - R_{\text{obs}}}{R_{\text{obs}}} = \ln \frac{1 - R}{R} + \frac{J}{k} \quad (5)$$

where

$$R_{\text{obs}} = \frac{C_b - C_p}{c_b} \quad (6)$$

$$R = \frac{C_m - C_p}{c_m} \quad (7)$$

$$k = b\gamma^a \quad (8)$$

where R_{obs} and R are the observable removal efficiency and true removal efficiency, respectively.

The mass transfer coefficient of the second group of humic substances, which occupies about 60% of total humic substances in Chitose River water, was determined by a combination of Eqs. (5)–(8). Fig. 7 shows the relationship between the mass transfer coefficient of the second group and the shear rate at the membrane surface. It shows that the mass transfer coefficient of the second group increases with an increasing shear rate. The relationship between them obtained from our experiments can be written as Eq. (9):

$$k = 2.0 \times 10^{-7} \gamma^{1.5} \quad (9)$$

The ratio of the concentration of the second group on the membrane surface to the concentration in the feed water can be calculated by a

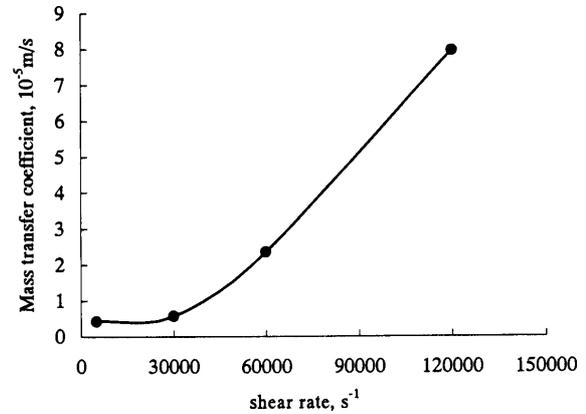


Fig. 7. Influence of shear rate on the mass transfer coefficient of humic substances of the second group.

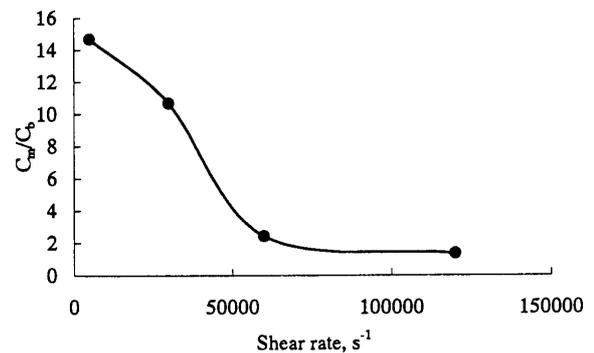


Fig. 8. Influence of shear rate on the ratio of concentration of humic substances of the second group at the membrane surface to the concentration in the feed water.

combination of Eqs. (4) and (9) as shown in Fig. 8. It shows that the concentration of the second group of humic substances on the membrane surface decreases with increasing shear rate. This result proves that the concentration polarization of humic substances can be reduced by increasing the shear rate at the edge of the membrane.

The water recovery rate is also an important parameter for water treatment. A common problem has been that the removal efficiency of solute decreases with increasing water recovery

rate during membrane filtration. The concentration of solute in the permeate can be predicted by a combination of Eqs. (5)–(7) and (9) as Eq. (10):

$$C_p = \frac{C_b \exp(J/k)(1-R)}{R + \exp(J/K)(1-R)} \quad (10)$$

Then the removal efficiency can be estimated by Eq. (11):

$$R_{\text{observed}} = 1 - \frac{\exp(J/k)(1-R)}{R + \exp(J/K)(1-R)} \quad (11)$$

The relationship between the water recovery rate of NF membrane filtration and the removal efficiency of humic substances in the second group was calculated by a combination of Eqs. (9) and (11) as shown in Fig. 9. It shows that the removal efficiency of the second group of humic substances decreases with increasing water recovery rate. The high removal efficiency of the second group could be sustained even when the water recovery rate reached 96%, if the membranes were vibrated with the maximum vibratory amplitude. The larger the vibratory amplitude, the higher the removal of humic substances. The correlation between removal efficiency in the second group and water recovery obtained in our experiments is also shown in Fig. 9. It shows that the concentration polarization model [Eq. (2)] predictions are consistent with the experimental results. These results also prove that the concentration polarization can be decreased by increasing the shear rate at the edge of the membrane, and it can be predicted by the concentration polarization model.

3.3. Reduction of concentration polarization of humic substances in MF membrane filtration

Fig. 10 shows the effect of membrane vibration on the removal efficiency of humic

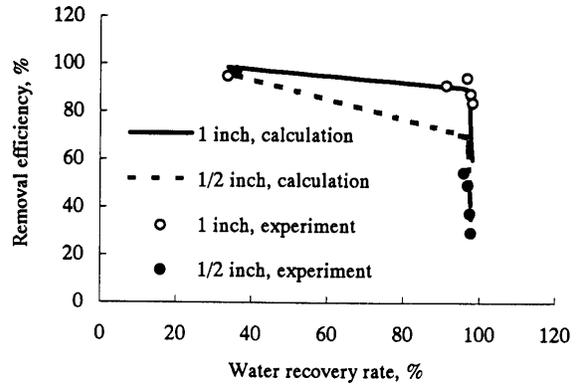


Fig. 9. Relationship between the water recovery of NF membrane filtration and the removal efficiency of humic substances in the second group.

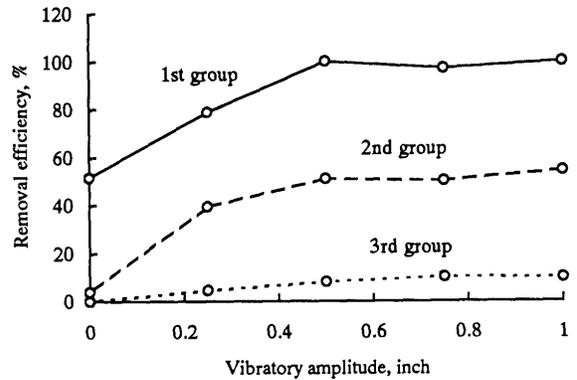


Fig. 10. relationship between the removal efficiency of humic substances in MF membrane and the vibratory amplitude.

substances in MF membrane filtration process. The removal efficiency increases with increasing shear rate at the edge of the MF membrane. It has been pointed out that the concentration of humic substances in Chitose River water was evaluated by E_{260} , which was measured after the river water was filtered through $0.45\mu\text{m}$ membrane filters. The humic substances are not usually removed by MF membrane filtration with a nominal pore size of $0.45\mu\text{m}$. However, as shown in Fig. 10, the removal efficiency of humic substances reached

60% when the MF membrane was vibrated at the maximum vibratory amplitude. The removal efficiency of humic substances in the three groups is also shown in Fig. 10. The humic substances in the first group can be completely removed at the maximum vibratory amplitude. The removal efficiency of humic substances in the second and third groups increases with increasing shear rate. One possible explanation of these results is that the shear rate has an effect on reducing the concentration polarization as discussed above. There may be some other mechanisms to explain the improvement of the removal of humic substances in MF membrane filtration process by membrane vibration, and more investigation of this phenomenon is needed.

4. The effect of shear rate on controlling membrane fouling

4.1. Cake layer formation on the membrane surface

Concentration polarization not only results in decreasing the removal of dissolved materials, but also results in increasing filtration resistances due to the formation of a concentration polarization boundary layer and a cake layer on the membrane surface. There are many existing models developed to predict flux decline during membrane filtration. The oldest model in the resistance model based on the cake filtration theory [7]. It has been successful in describing flux decline during dead-end MF/UF membrane filtration of particulate suspensions. It has also, however, been considered that this model cannot be applied to cross-flow filtration where the feed solution continuously recirculates. This is because after the initial cake build-up the cake growth on the membrane surface can be arrested by the action of the tangential flow [8]. In membrane filtration for river waters treatment, the membrane filtration process is confronted with a mixture of suspended colloids and natural

organic materials such as humic substances. Furthermore, the suspended colloids and natural organic materials in waters have a wide size distribution, which results in differing diffusion action near the membrane surface. This means that small particles are deposited into the initial cake layer as the permeate flux declines. The porosity of cake layer decreases with the deposition of small particles, which results in an increase in the resistance of the cake layer. Therefore, in membrane filtration for river waters treatment, the cake layer thickness growth may be arrested after initial cake build-up, but the cake layer resistance cannot be arrested, even in a cross-flow membrane filtration process. Based on the above discussion, the resistance model based on the cake filtration theory may also apply for the river water treatment in the cross-flow filtration process.

Previous research carried out by the authors [1,9,10] pointed out that the UF membrane fouling was dominated by the cake layer formation caused by accumulation of dissolved organic materials and suspended colloids in the raw water. The particles are driven to the membrane surface by the permeate flow to form a cake layer on the membrane surface, unless the shear rate is sufficiently high to prevent cake formation. The undetachable cake layer, which cannot even be removed by back washing and/or air scrubbing, accumulates on the membrane surface in every filtration cycle and results in membrane fouling in the long-term operation. In the cross flow UF membrane filtration under a constant pressure, the filtration process is divided into the following two stages: accumulation stage of the undetachable cake layer, and a second stage where accumulation and detachment of cake layer reach equilibrium. When the filtration process reaches the equilibrium stage, the flux becomes too small and chemical cleaning is needed. In the dead-end UF membrane filtration under a constant permeate flux, the filtration process is divided into the following two stages:

accumulation stage of the undetachable cake layer, and compression stage of the accumulated cake layer. When the filtration process reaches the compression stage, the transmembrane pressure becomes too high and chemical cleaning is needed. The formation of the undetachable cake layer is influenced by the concentration and size distribution of suspended particles and humic substances in the raw water by filtration pressure and by permeate flux. Based on the cake filtration theory, the undetachable cake layer model was developed by the authors [8]. It has been successful in evaluating the membrane fouling and in predicting the resistance of the undetachable cake layer during continuous UF membrane filtration of river water with hydraulic cleaning such as backwash and/or air scrubbing.

The authors [10] also presented three methods for controlling membrane fouling caused by cake formation:

1. Pre-coagulation to flocculate foulants to form micro-flocs, resulting in higher back transport velocity and lower cake specific resistance.
2. Enhancement of shear rate at the membrane surface to prevent the attachment of foulants by increasing back transport velocity.
3. Improvement of the hydraulic cleaning to remove the accumulated cake layer on the membrane surface.

It was pointed out by the authors [11] that membrane fouling in the cross flow UF membrane filtration under a constant pressure can be controlled effectively by pre-coagulation with an Al dosage which coagulates the high molecular humic substances. However, the success of pre-coagulation on controlling the membrane fouling decreases if the Al dosage is more than the dosage needed for coagulating the high molecular humic substances. In the dead-end UF membrane filtration under a constant permeate flux, pre-coagulation is not effective for controlling membrane fouling.

The effect of the enhancement of the shear rate at the NF membrane surface to prevent the cake layer formation is discussed below.

4.2. Effect of shear rate on controlling cake layer formation in NF membrane filtration

A series of experiments was conducted to examine the effect of shear rate on controlling the cake layer formation. The permeate flux decline of NF membrane is shown in Fig. 11. It shows that the permeate flux of NF membrane increased with increasing vibratory amplitude. This is because the strong shear rate produced by high vibratory amplitude prevented foulants such as suspended particles and the humic substances from accumulating on the NF membrane.

In the long-term continuous membrane filtration under a constant pressure without any hydraulic cleaning, the undetachable cake model can be written as Eq. (12):

$$\frac{P}{\mu J} = R_0 + R_c = K_c \frac{V}{A} + \frac{P}{\mu J_0} \quad (12)$$

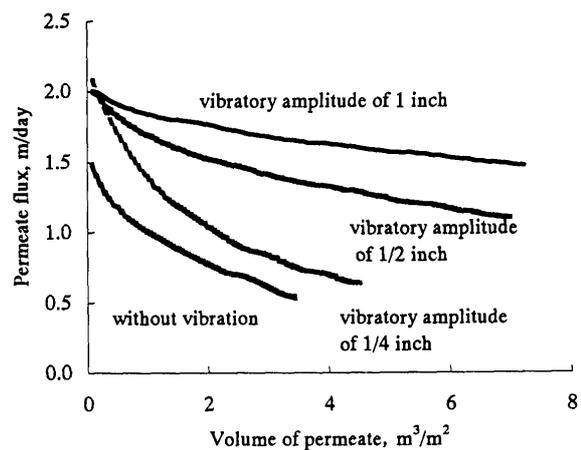


Fig. 11. Decline of permeate flux of the NF membrane with and without vibration.

where P is filtration pressure (Pa), J_0 is the initial permeate flux of the new membrane (m/s), R_0 is the resistance of the membrane (m^{-1}), V is the volume of the permeate (m^3), A is the area of the membrane (m^2) and K_c is the specific resistance coefficient of the cake layer accumulated on the membrane surface (m^2). The specific resistance coefficient of the cake layer can be defined as follows:

$$K_c = \alpha C \quad (13)$$

where α is the well-known specific resistance (m/kg) and C is the concentration of the materials found in the feed water form the cake layer (kg/m^3). C is difficult to determine for the river water filtration process, so we defined the specific resistance coefficient to evaluate the membrane fouling in our research.

Fig. 12 shows the results of analysis of the experimental data using the cake formation model [see Eq. (12)]. It shows that there is a good linear relationship between the filtration resistances and the accumulative permeate volume. The specific resistance coefficient decreases with increasing vibratory amplitude of the membrane. These results indicate that the cake formation on the NF membrane surface results in serious membrane fouling which can be effectively controlled by membrane vibration.

The back transport model can be used to explain the mechanisms of controlling membrane fouling by increasing the shear rate at the edge of the membrane. Three back transport models have been developed: the well-known Brownian diffusion for small molecular substances [12], the shear-induced diffusion model for macromolecules [13], and the lateral migration model for colloids [14]. These back transport models predict that the steady-state permeate flux increases with shear rate and particle size.

For the size distribution range of colloids and humic substances in river water, Brownian

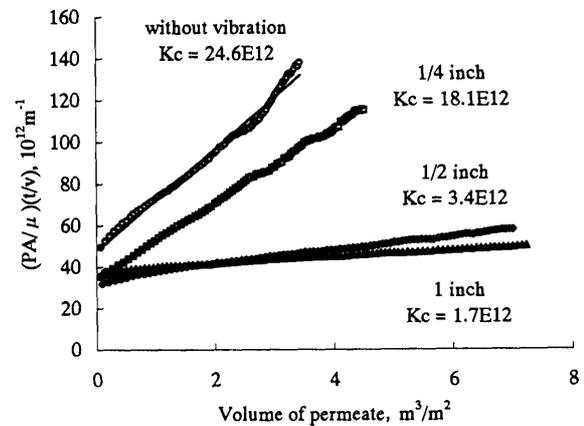


Fig. 12. Analysis of permeate flux data by the cake filtration model.

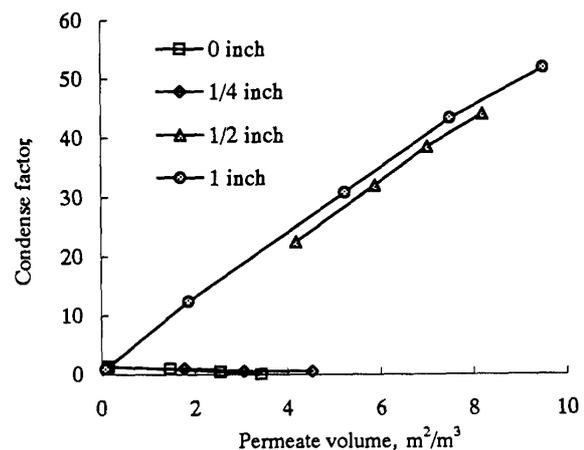


Fig. 13. Condense factor of humic substances in the first group during NF membrane filtration.

diffusion and the shear-induced diffusion are important to evaluate the back transport away from the membrane surface. As the particle size or molecular weight of the substances decreases, the Brownian diffusion coefficient increases, whereas the shear-induced diffusion coefficient decreases. The effective diffusion coefficient is the sum of those two diffusion coefficients. Figs. 13–15 show the condense factors of humic substances in the three groups during NF

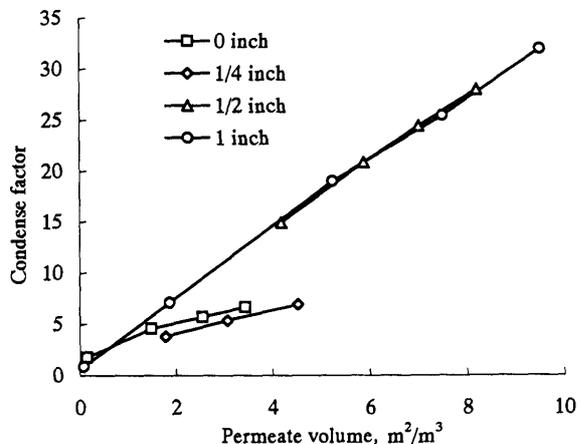


Fig. 14. Condense factor of humic substances in the second group during NF membrane filtration.

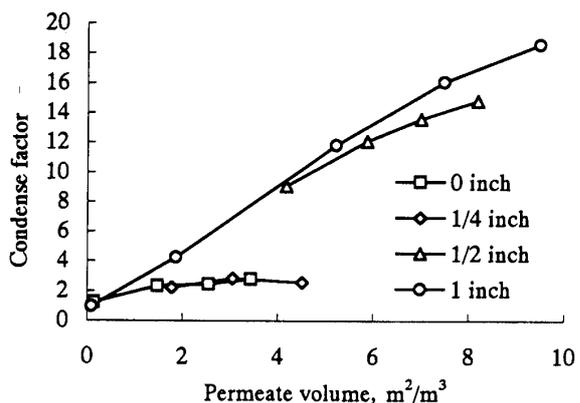


Fig. 15. Condense factor of humic substances in the third group during NF membrane filtration.

membrane filtration of Chitose River water. They show that the condense factors of humic substance in the three groups increase with increasing vibratory amplitude. These results indicate that the humic substances back transport away from the membrane surface to the feed water and transport velocities of humic substances increase with increasing shear rate. It produces evidence to indicate that the shear-induced diffusion coefficient increases with increasing shear rate. Fig. 13 shows that humic

substances in the first group cannot be concentrated in the feed water when the membrane is vibrated at a vibratory amplitude of less than 1/4". It indicates that humic substances in the first group cannot be back transported by only Brownian diffusion because its Brownian diffusion coefficient is too small. However, the humic substances in the second and third groups can be concentrated in feed water (see Figs. 14 and 15) even when the membrane is vibrated at a vibratory amplitude of less than 1/4". This indicates that humic substances in the second and third groups can be back transported by only Brownian diffusion because their Brownian diffusion coefficients are larger than those of the humic substances in the first group.

5. Conclusions

Concentration polarization not only results in a decrease of the removal of dissolved materials, but also in increase of filtration resistances. This paper dealt with the results from experiments concerning the effects of an increasing shear rate at the edge of the membrane on reducing concentration polarization and on controlling membrane fouling. Concentration polarization of humic substances in NF and MF membranes can be reduced by increasing the shear rate. This has been proved by the increase in mass transfer coefficient and the decrease in the concentration on the membrane surface with increasing shear rate. The concentration polarization model can successfully predict the removal efficiency of humic substances. The high removal efficiency of humic substances in NF membrane filtration processes can be sustained even when the water recovery rate reaches 96% if the membranes are vibrated with the maximum vibratory amplitude.

A cake layer formation on the NF membrane surface due to deposition of suspended colloids and humic substances dominates NF membrane fouling. NF membrane fouling can be evaluated

by the cake filtration model and controlled by increasing the shear rate. Humic substances in the first group are transported away from the membrane surface by the shear-induced diffusion. Humic substances in the second and third groups are transported away from the membrane surface not only by the shear-induced diffusion, but also by Brownian diffusion.

Acknowledgements

This research has been supported by the Core Research for Evolutionary Science and Technology (CREST) of Japan Science and Technology Corporation (JST) and by the Advanced Aqua Clean Technology 21st Centenary (ACT21) research project of the Japanese Ministry of Health and Welfare.

References

- [1] R. Bian, Y. Watanabe and N. Tambo, *J. JWVA*, 785 (2000) 12.
- [2] AWWA Membrane Technology Research Committee, *J. AWWA*, 90 (1998) 91.
- [3] N. Tambo and T. Kamei, *J. JWVA*, 62 (1993) 28.
- [4] K. Takada, K. Yamamoto, R. Bian and Y. Watanabe, *Desalination*, 117 (1998) 273.
- [5] Y. Konishi et al., *Sjinko Pantec Eng. Reports*, 42 (1999) 28.
- [6] E. Matthiasson and B. Sivik, *Desalination*, 35 (1980) 59.
- [7] J. Hermia, *Ins. Chem. Eng.*, 60 (1982) 183.
- [8] R.H. Davis, *Sep. Purif. Methods*, 21 (1992) 75.
- [9] R. Bian, Y. Watanabe and N. Tambo, *J. JWVA*, in press.
- [10] R. Bian, Y. Watanabe, G. Ozawa and N. Tambo, *J. JWVA*, 67(1) (1998) 16.
- [11] R. Bian, Y. Watanabe and N. Tambo, *J. JWVA*, in press.
- [12] M.C. Porter, *Ind. Eng. Chem. Prod. Res. Dev.*, 11(3) (1972) 234.
- [13] G. Grem and G. Belfort, *Desalination* 35 (1980) 129.
- [14] R.H. Davis and D.T. Leighton, *Chem. Eng. Sci.*, 42(2) (1987) 275.