Simulation of membrane fouling considering mixed liquor viscosity and variation of shear stress on membrane surface

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ABSTRACT

Simulation of membrane fouling in MBR was conducted considering accumulation, detachment and consolidation of extracellular polymeric substances accumulated on membrane surface. The fluctuation of shear stress working on membrane surface and the influence of the viscosity of mixed liquor were considered for the evaluation of shear stress. A flat-sheet-type membrane module was used and the change of trans-membrane pressure was measured in a laboratory-scale MBR reactor. Shear stress working on membrane surface caused by aeration was measured by a shear force sensor changing viscosity of bulk liquid. Effective shear stress on membrane surface was defined in the model as the sum of time-averaged shear stress and three times of standard deviation. The increase in the trans-membrane pressure was accurately simulated by the developed model suggesting validity of the developed fouling model and the idea of the effective shear stress on membrane surface.

Key words | flat sheet membrane, MBRs, membrane fouling, shear stress

INTRODUCTION

Membrane bioreactors (MBRs) are processes that involve the separation of activated sludge from treated water using membrane separation. MBRs are now widely used in many kinds of wastewater treatment plants because they have merits such as complete removal of suspended solids from effluent, better nutrient and organic removal efficiency, and smaller footprint.

However, the problem of membrane fouling must be solved to get treated water continuously and stably through membrane thereby lowering maintenance cost and giving MBRs higher applicability to varieties of treatment processes. Although membrane fouling could be solved by periodical chemical cleaning of the membrane, the cleaning interval is determined only from experiences of operations without theoretical considerations. Too much frequent chemical cleanings would result in not only deterioration of membrane material but also increases of operational costs. If the process of membrane fouling is accurately predicted, the optimal clean interval can be determined thereby making the MBR processes more efficient.

Nagaoka et al. (1996, 1998) developed a model to simulate membrane fouling processes considering production of biological metabolic substances, their attachment to and detachment from the membrane surface, friction between the accumulated substances and the membrane surface as well as the shear stress acting on the membrane suggesting the chemical cleaning interval is dependent on the shear stress on membrane.

However, there has been little research on the simulation of trans-membrane pressure increase considering measured shear stress values for parameters in a membrane fouling model. The objective of this study is to simulate membrane fouling processes, which includes the accumulation, detachment and consolidation of bacterial extracellular polymers (EPS) on a membrane surface. For the evaluation of the shear stress on the membrane surface, which influences the detachment rate of the foulants from the membrane surface, the fluctuation of the shear stress and the influence of the viscosity of the mixed liquor on the magnitude of the shear stress were considered in the fouling model.
MATERIALS AND METHODS

Experimental setup (measurement of the shear stress)

Figure 1 shows a schematic diagram of the experimental setup used for measuring the shear stress induced by the flow of rising air bubbles. On a wall of a rectangular tank made of transparent acryl, a shear force sensor (SSK Co. Ltd., Japan: S10W-1) of the diameter 10 mm was set. The shear stress was measured directly changing air flow rate and the viscosity of water. A PVC pipe of 8 mm diameter with 53 pin holes of 0.5 mm diameter dig regularly on the wall was used as an air diffuser being connected to an air pump and set near the bottom of the tank to supply air bubbles. The sensor was connected to a personal computer through an analogue-to-digital converter for taking time-series data of the shear force variation at 100 Hz for 40.96 s. The sampling number was therefore 4,096. The measured shear force was divided by the area of the sensor to calculate shear stress. The viscosity of the water was changed by dissolving methyl cellulose.

Experimental setup (a laboratory scale MBR)

Figure 2 shows a diagram of the other experimental setup used in this research. A rectangular tank (45 cm × 97 cm × 45 cm) made of transparent acryl was used as the aeration tank, in which six flat-sheet-type micro-filtration membrane modules of chlorinated poly-ethylene, with a pore size of 0.4 μm, were submerged. Concentrated synthetic wastewater (substrate) was fed into the reactor using a tube pump. The main components of the substrate were acetic acid and ammonium chloride. The organic loading rate to the reactor was set constant at 0.6 g-TOC L⁻¹ day⁻¹ during the course of the operation.

Two air diffusers were set below each membrane module so that rising air bubbles could provide the membrane surface with a shear stress effective for removing attached sludge from the membrane. Different air flow rates were set for the membrane modules to investigate their influence on the permeate flux. The air flow rate was 7.5 L/min/slit for three membrane sheets and 17.5 L/min/slit for other three membrane sheets, where “slit” means the space between the walls (membrane sheets) through which air bubbles rise (equal to 1.3 cm in this experiment). The permeate flux was set at...
0.53 m day\(^{-1}\) for each membrane module by controlling the rotational speed of the tube pumps. Activated sludge taken from a municipal wastewater treatment plant was used as seeding sludge for the experiment.

### Model Equations

A simple mathematical model developed by Nagaoka et al. (1998) was used to simulate the change in pressure and filtration resistance during operation, because the model was thought to be useful for the prediction of the reactor performance and/or the optimisation of the operational parameters.

The change in the concentration of the suspended bacteria (mixed liquor suspended solids - MLSS) was modelled in a simplified manner as follows:

$$\frac{dx}{dt} = Y \cdot L - k_{de} \cdot x$$  \hspace{1cm} (1)

where \(x\) is the MLSS concentration (g/L), \(Y\) is the yield factor (g-MLSS/g-TOC), \(L\) is the TOC volumetric loading rate (g m\(^{-3}\) day\(^{-1}\)), \(k_{de}\) is the death rate of the MLSS (day\(^{-1}\)) and \(t\) is the time (day).

EPS, which was considered to be a main foulant of MBRs, was modelled to be produced with the growth of bacteria at a certain rate and decomposed obeying first-order kinetics:

$$\frac{dp}{dt} = \beta \cdot Y \cdot L - k_{dp} \cdot p$$  \hspace{1cm} (2)

where \(p\) is the suspended EPS concentration (g m\(^{-3}\)), \(\beta\) is the ratio of the produced EPS to the increase in the MLSS (g-EPS/g-MLSS) and \(k_{dp}\) is the degradation rate of EPS (day\(^{-1}\)).

EPS was modelled to accumulate on the membrane by advection (i.e. the mass flow of water through the membrane) and to be detached by the shear stress caused by the cross flow of water and bubbles. The balance of the forces, the shear stress and the static friction caused by the suction pressure, was considered to model the detachment rate of EPS. Overall EPS behaviour on membrane surface was therefore described as follows:

$$\frac{dm}{dt} = J \cdot p - k_{dm} \cdot m$$  \hspace{1cm} (3)

$$k_{dm} = \gamma (\tau_m - \lambda_m \cdot \Delta P) \quad (k_{dm} \geq 0)$$  \hspace{1cm} (4)

where \(m\) is the EPS density on the membrane surface (kg m\(^{-2}\)), \(J\) is the flux (m day\(^{-1}\)), \(k_{dm}\) is the detachment rate of EPS from the membrane surface (day\(^{-1}\)), \(\gamma\) is a constant (day\(^{-1}\) Pa\(^{-1}\)), \(\tau_m\) is the shear stress (Pa), \(\lambda_m\) is the static friction coefficient (–) and \(\Delta P\) is the trans-membrane pressure difference (Pa).

The accumulated EPS on the membrane consolidates slowly, via the suction pressure. The consolidation process was assumed to follow first-order kinetics approaching an ultimate value which is a function of the trans-membrane pressure, \(P\):

$$\frac{dx}{dt} = k_s(x_s - x)$$  \hspace{1cm} (5)

$$x_s = x_0 + x_p \cdot \Delta P$$  \hspace{1cm} (6)

where, \(x\) is the specific resistance of the EPS (m kg\(^{-1}\)), \(k_s\) is the rate constant of the consolidation process (day\(^{-1}\)), \(x_s\) is the ultimate value of \(x\) (m kg\(^{-1}\)), \(x_0\) is the value of \(x\) when \(P = 0\) (m kg\(^{-1}\)), and \(x_p\) is a constant (m kg\(^{-1}\) Pa\(^{-1}\)).

The total filtration resistance (as defined in Equation 7) is expressed as the sum of the membrane resistance and the resistance given by the accumulated EPS:

$$J = \frac{P}{\mu_w \cdot R}$$  \hspace{1cm} (7)

$$R = x \cdot m + R_{memb}$$  \hspace{1cm} (8)

where \(R\) is the filtration resistance (m\(^{-1}\)), \(\mu_w\) is the viscosity of the permeate (Pa s), and \(R_{memb}\) is the membrane resistance (m\(^{-1}\)).

The mixed liquor viscosity was modelled to obey Equation 9 (X. Li & X. Wang 2006):

$$\mu_L = 1.05 \mu_w e^{0.08c}$$  \hspace{1cm} (9)

where \(\mu_L\) is the viscosity of the mixed liquor, \(\mu_w\) is the clean water viscosity and \(C\) is the MLSS concentration.

Equations (1) to (8) were solved numerically as an initial condition problem using the Runge–Kutta method with a time interval of 0.5 days.

The model parameter values used in the calculation were as follow:

\[
\begin{align*}
Y &= 0.4 \text{g-MLSS/g-TOC}, \quad k_{de} = 0.03 \text{day}^{-1}, \\
\beta &= 0.4 \text{g-EPS/g-MLSS}, \quad k_{dp} = 0.2 \text{day}^{-1} \text{Pa}^{-1}, \\
\gamma &= 0.07 \text{day}^{-1} \text{Pa}^{-1}, \quad \lambda_m = 0.00001, \quad k_s = 0.028 \text{day}^{-1}, \\
x_0 &= 1 \times 10^{11} \text{mg kg}^{-1}, \quad x_p = 5.9 \times 10^{11} \text{mg kg}^{-1} \text{Pa}^{-1}, \\
\mu &= 0.00000000972 \text{Pas}, \quad J = 0.55 \text{m day}^{-1}
\end{align*}
\]
EPS extraction and molecular weight distribution measurement

For EPS extraction from the cell, the cation exchange resin (CER) extraction method (Frolund et al. 1996) was applied. The mixed liquor sample (30 mL) was centrifuged at 3000 g for 10 min and the sedimentation was mixed with a buffer solution (2 mM Na$_3$PO$_4$, 4 mM NaH$_2$PO$_4$, 9 mM NaCl, 1 mM KCl, pH 7.0) to be centrifuged again at 3000 g for 10 min. The sedimentation was mixed with the buffer solution to make it up to 20 mL. CER was then added to the solution (at the rate of 100 g of CER for 1 g of volatile suspended solids (VSS) and stirred for 1.5 hours at 280 rpm for extraction. The CER and the sludge fraction were separated from the liquid fraction by centrifuging at 3000 g for 10 min. The supernatant was centrifuged again at 14000 g for 10 min and the supernatant was analysed for TOC. For molecular weight fractioning, Sephacryl S-300HR (molecular weight range 14000–1,500,000 Da) was used with a buffer solution of (66.7 mM KH$_2$PO$_4$ and 66.7 mM Na$_2$HPO$_4$.12 H$_2$O). Each fraction was analysed for TOC and UV absorbance.

RESULTS AND DISCUSSIONS

Influence of the viscosity on the shear stress

Figure 3 is an example of the time-series variation data for the shear stress (viscosity $= 12$ mPa s, air flow rate $= 17.5$ L/min). The shear stress variations show strong fluctuations that might be caused by strong turbulence or by the interactions between air bubbles and the surface.

Figure 4 shows the relationship between the viscosity and the time-averaged value of the shear stress. It was found that the time-averaged shear stress increased with increases in the viscosity of the mixed liquor and the air flow rate. The two experimental conditions were modelled as follows:

\[ \tau_{7.5\text{L/min}} = 0.1112\mu_L + 4.0588 \]
\[ \tau_{17.5\text{L/min}} = 0.1229\mu_L + 5.7155 \]

Figure 5 shows the relationship between the viscosity and the standard deviation of the variation of the shear stress, where the influence of the viscosity was found to be larger with the higher air flow rate. The standard deviations of the variation of the shear stress were therefore modelled as follows:

\[ \sigma_{7.5\text{L/min}} = 0.0158\mu_L + 0.2793 \]
\[ \sigma_{17.5\text{L/min}} = 0.0399\mu_L + 0.2298 \]

It is reported that for the evaluation of the shear stress on membrane surface, not only time-averaged values but also the variation should be considered (Nagaoka et al. 2003).
The effective shear stress was therefore set as the time-averaged shear stress plus three times the standard deviation (Equation 10) so that the fluctuation of the shear stress in the simulation of membrane fouling could be considered.

\[ \tau_{\text{effective}} = \tau + 3\sigma \]  

(10)

where \( \tau \) is time-averaged shear stress and \( \sigma \) is standard deviation of the variation of shear stress.

**Simulation of membrane fouling**

**Figure 6** shows the measured and the calculated changes in the MLSS concentration. Starting from about 6 g/L, it continued to increase slowly for 12 days, the trend of which is well simulated by the model at the initial state although the measured MLSS concentration decreased afterwards.

**Figure 7** shows the measured and the calculated changes in the EPS concentration during the experiment. The EPS concentration in the reactor did not increase much after 18 days, which was in good agreement with the simulated curve.

**Figure 8** shows the measured and the calculated changes in the suction pressure in the reactor. The sudden increase in the pressure (with an air flow rate of 7.5 L/min/slit) after 8 days is well simulated by this model. However, an increase in the pressure with an air flow rate of 17.5 L/min/slit is not well simulated by this model implying that the shear stress in this condition is not accurately evaluated.

In order to increase the magnitude of the influence of the air flow rate on the effective shear stress, the time-averaged value plus 4.5 times the standard deviation (instead of 3 times) was adopted for the 17.5 L/min/slit scenario, the calculation result of which is shown in **Figure 9**, where both of the measured trans-membrane pressure curves are well simulated by the model, suggesting that consideration of 4.5 times of standard deviation of shear stress fluctuation is more appropriate for the model in this experiment.

The results of these simulations (**Figure 8** and **Figure 9**) suggest the validity of the fouling model developed in this research, where the influence of the viscosity on the shear stress and the time-series variation of the shear stress were
considered. However, as both figures suggest, the evaluation of the effective shear stress is very influential on the accuracy of the fouling simulation. More research might be necessary for the evaluation the time-series variation of the shear stress.

**CONCLUSIONS**

A laboratory scale experiment was conducted to simulate membrane fouling. Shear stress on membrane surface was also measured changing air ow rate and the viscosity of water. Time-series data of the shear stress showed strong fluctuations, which was caused either by strong turbulence or by the interactions between air bubbles and the surface. Effective shear stress was therefore defined in the model as the sum of the time-averaged value stress plus three times the standard deviation.

The increase in the trans-membrane pressure was well simulated by the developed model. However, as the effective shear stress was found to be very influential on the fouling simulation, more research might be necessary for the evaluation of the fluctuation of the shear stress on membrane.

**REFERENCES**


