Effect of bubble flow velocity on drag-force and shear stress working on submerged hollow fibre membrane

Water Science & Technology **Vol 54 No 10 pp 185–192** © IWA Publishing 2006

H. Nagaoka*, M. Kurosaka*, N. Shibata and M. Kobayashi****

*Department of Civil Engineering, Musashi Institute of Technology, Tamazutsumi 1-28-1, Setagaya-ku, Tokyo, 158-8557, Japan (E-mail: *hnagaoka@sc.musashi-tech.ac.jp*)

**Mitsubishi Rayon Engineering Co., Ltd, 4-1-2, Ushikawa-dori, Toyohashi, Aichi, 440-8601, Japan

Abstract This study is aimed at elucidating the mechanism by which rising air bubbles induce shear stress on hollow fibre membrane surfaces. Shear stress on hollow fibre membrane surfaces (laterally-set and vertically-set) caused by aeration was measured directly using a two-direction load sensor. In the laterally-set hollow fibre module, time-averaged upward-direction shear stress on the membrane surface was compared to theoretical shear stress values considering the effect of water flow on membrane surface. Measured time-average shear stress values were almost 200 times larger than theoretical values implying strong interactions between bubbles and solid surface. In the vertically-set membrane module, velocity measurement of bubble flow using laser Doppler velocimeter revealed that drag force working on membrane surface was closely related to upward-direction water velocity. Also fluctuation of drag force and shear force on membrane surface was found to be related to velocity fluctuation (turbulence).

Keywords Bubble flow; hollow fibre membrane; laser doppler velocimeter; membrane bioreactor; shear stress

Introduction

In submerged membrane bioreactors, shear stress caused by aeration on membrane surface is a very important factor to determine the performance of the reactor. More air flow rate of aeration can maintain the reactor with longer chemical cleaning interval. However, higher air flow supply would result in high electricity consumption rate. It is therefore very important to know how air flow rate influences the magnitude of the shear stress from viewpoint of the maintenance of the membrane bioreactor. Several research studies have been conducted concerning interaction between bubble flow and a wall. Moursali *et al.* (1994) measured distribution of void ratio water velocity and shear stress on a wall and concluded that behaviour of bubbles near a wall influences the magnitude of shear stress on a wall. Ozaki and Yamamoto (2001) studied the hydraulic effects on sludge accululation on membrane surface in crossflow filtration and suggested the importance of shear stress on membrane surface. Nakoryakov *et al.* (1996) reported that shear stress on a wall is greater in liquid-air two phase flow than in water phase flow. Laborie *et al.* (1998) reported that slug flow of air and water inside a hollow fibre can maintain stable permeate flux. Le-Clech *et al.* (2003) studied the optimization of aeration in a submerged MBR defining minimum air velocity requirement. Nagaoka *et al.* (2001, 2003) measured directly shear stress on a wall in bubble flows and concluded that interaction between bubbles and a wall could induce strong shear stress on a wall and is an important factor for submerged MBRs using flat-sheet membranes to maintain stable flux. However, very little research has been conducted concerning shear stress on hollow fibres in submerged MBR. This research is aimed at measuring shear stress on the outside surface of hollow fibres in bubble flow and elucidating the mechanism of the induction of the shear stress as basic information for the better maintenance of the MBRs.

doi: 10.2166/wst.2006.818

Materials and methods

Experiment for vertically-set hollow fibre

Figure 1 shows a schematic diagram of an experimental set-up used for measuring shear stress working on vertically-set hollow fibre membranes induced by bubble flow (aeration). Two types of polyethylene hollow fibre membrane (outer diameter: 0.54 mm and 0.78 mm) were used for the experiment. Hollow fibres of 380 mm long were set vertically in a tank filled with tap water with one end of the fibre connected to a two-direction loads sensor (SSK Co. Ltd., Japan: LV30-1, range: 1 kgf) set on the bottom while the other end was fixed at the middle of the tank so that the fibre was fixed in the tank with tension. By the load sensor, two-direction total force (upward direction and lateral direction) working on the hollow fibres was measured. Air diffuser was set just below the fibre so that air ejected from the diffuser touches the hollow fibre.

Table 1 shows experimental conditions. In Case 1 and Case 3, just one hollow fibre was connected to the load sensor to measure the forces when one hollow fibre is set in a bubble flow without any interactions with other fibres. In Case 2 and Case 4, three hollow fibres were connected to the load sensor to investigate the effect of interactions between hollow fibres. Air flow rate was changed between 5.0–20 L/min.

Output from the load sensor was stored in a personal computer through an A/D converter to measure time-series data. The output (tension force at the bottom of the fibres) was divided by total surface area of the membrane to calculate shear stress on the hollow fibre membrane surface. Calibration of the sensor was conducted before every measurement stopping the supply of air considering the condition as a zero-shear stress condition.

Experiment for laterally-set hollow fibre

Figure 2 shows a schematic diagram of an experimental setup for measuring shear stress working on laterally-set hollow fibre (polyethylene, outer diameter: 0.54 mm) membranes induced by bubble flow. The module was submerged in a tank which was filled with tap water and the two-direction loads sensor (SSK Co. Ltd., Japan: LV30-1, range: 1 kgf) was set at two places (top and bottom positions) as is shown in the figure. Figure 3 shows how the sensor was connected to the hollow fibre and how shear force and drag force on the membrane could be measured. Oba (1985) measured velocity of bubble flow

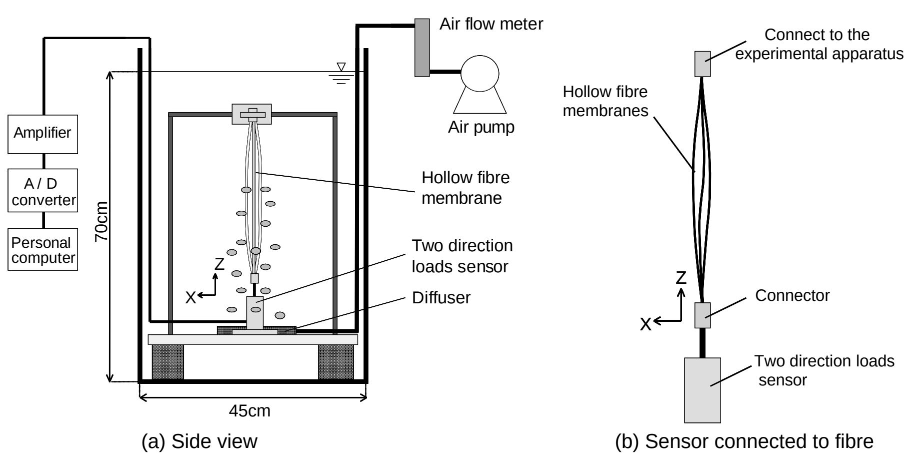

Figure 1 Schematic diagram of an experimental set-up used for measuring shear stress on vertically-set hollow fibre membranes induced by bubble flow

Table 1 Experimental condition for vertically-set membrane

Air flow-rate (L/min)	**5.0–20**			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Outer diameter (μm)	540	540	780	780
Inner diameter (μm)	350	350	540	540
Length (mm)	378	380	377	371
Number of membranes	1	3	1	3

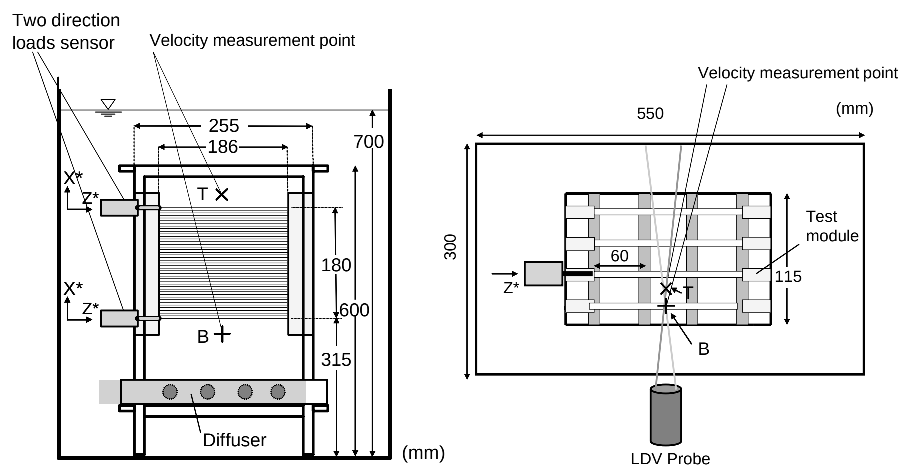

Figure 2 Schematic diagram of an experimental set-up used for measuring shear stress on laterally-set hollow fibre membranes induced by bubble flow

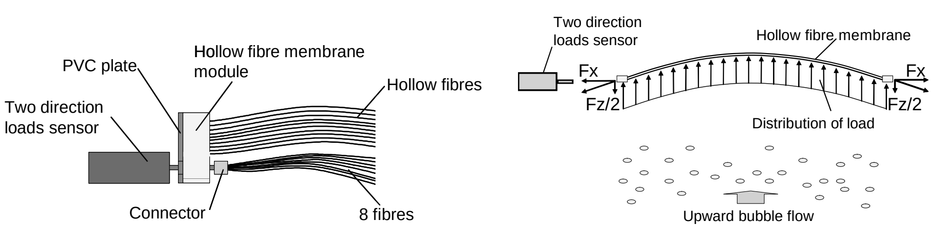

Figure 3 Connection of the load sensor to the laterally-set hollow fibre membrane

successfully using a laser Doppler velocimeter. In this research for evaluating velocity and turbulence of bubble flow near the membrane module, velocity (two-direction) was measured at two points as is shown in the figure using a laser Doppler velocimeter.

Results and discussion

Vertically-set hollow fibre

Shear stress variation. Figure 4 is an example of time-series variation data (Lateral (X)-direction and Upward (Z)-direction) in one-hollow-fibre cases of 540 μm thickness. Time-series data of upward (Z)-direction shear stress showed strong fluctuation, which is caused by turbulent flow around the hollow fibre and also by the effect of interaction between bubbles and solid surface (membrane surface). Lateral (X)-direction drag force also showed strong fluctuation, the intensity of which was about one tenth of the intensity

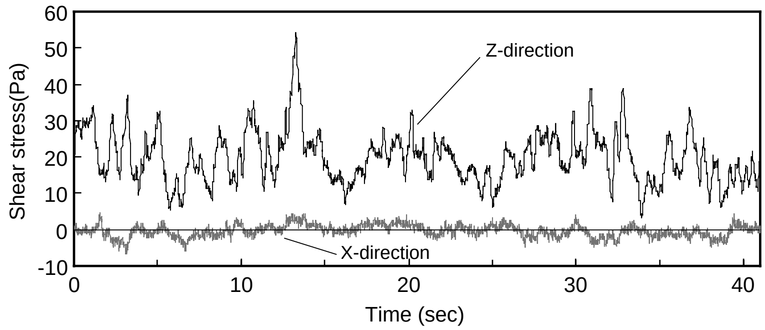

Figure 4 Shear stress variation (outer diameter: 540 µm, one hollow fibre, air flow-rate: 20 L/min)

of upward-direction. In all the cases of the experiment, time-averaged value of Z-direction was larger than that of X-direction value.

Time-averaged shear stress value (Z-direction). Figure 5 shows relationship between air flow-rate and time-averaged Z-direction shear stress value with the standard deviation of fluctuation shown as width of bars. Time-averaged shear stress increases with the increase of air flow rate almost linearly with one exception of three 540 µm fibres case. In one hollow fibre cases, time-averaged shear stress value was almost double that of three fibres cases. This might be because bubble flow cannot go through in-between fibres thereby reducing the influence of direct bubble flow effects. Influence of thickness of hollow fibre on time-averaged shear stress was not clear in these conditions.

Evaluation of effect of upward water velocity on shear stress. Shear stress acting on hollow fibre membrane surfaces in bubble flow is the sum of shear stress caused by upward water velocity and direct interactions between bubbles and membrane surface. In order to evaluate these two effects, shear stress caused by friction of water velocity was calculated. If the bubble flow is assumed to be single-phase liquid flow over

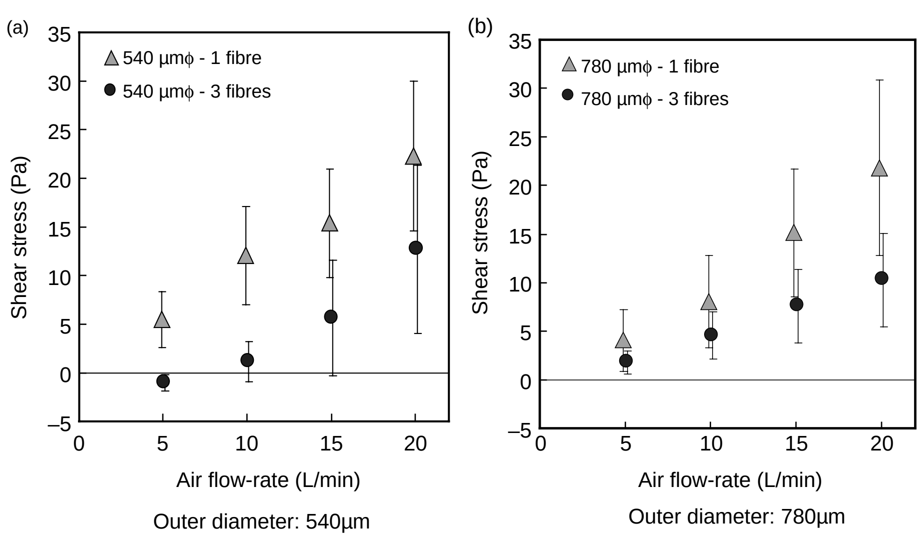

Figure 5 Relationship between air flow-flux and time-averaged shear stress value. Length of bars shows standard deviation

hydraulically smooth surface, Equations (1), (2) and (3) can be used to calculate shear stress acting on the wall:

$$\tau = \frac{f}{8}\rho\bar{v}^2 \qquad (1)$$

$$f = 0.316\,\mathrm{Re}^{-1/4} \qquad (2)$$

$$\mathrm{Re} = \frac{\bar{v}D}{\nu} \qquad (3)$$

where τ: shear stress, f: friction factor, ρ: water density, $\bar{v}$: mean upward water velocity, Re: Reynolds number, ν: kinematic coefficient of viscosity, D: width of the bubble flow.

Bubble flow width D was determined to be 18 cm according to observation by VTR. Mean upward water velocity was measured by VTR image using a tracer (5 mm × 5 mm). Substituting the measured water velocity values to equations (1) and (3), shear stress by water flow was calculated.

Figure 6 shows relationship between calculated shear stress generating by water flow and measured time-averaged shear stress (fibre outer diameter: 540 μm, one hollow fibre). It is shown that measured values are almost 200 times larger than calculated values suggesting that shear stress on a hollow fibre membrane surface is caused by direct interaction between bubbles and fibres and the effect of water flow is negligible.

Laterally-set hollow fibre membrane

Velocity and stress variation. Figures 7 and 8 show examples of velocity and stress variation measured at the bottom part of the membrane module. Both sets of data show strong fluctuation and interaction between velocity variation (turbulence) and stress variation is suggested.

Figure 9 shows comparison of measured and simulated time-averaged drag stress on hollow fibre. For the simulation, the following model was employed;

$$\bar{\tau} = \frac{1}{2}\rho \quad C_D\bar{v}^2 \qquad (4)$$

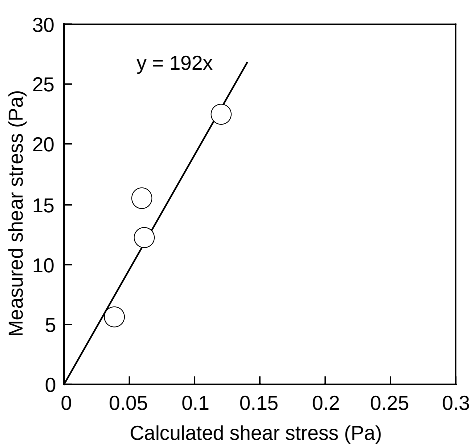

Figure 6 Relationship between calculated wall shear stress and measured time-averaged shear stress (outer diameter: 540 μm, one hollow fibre)

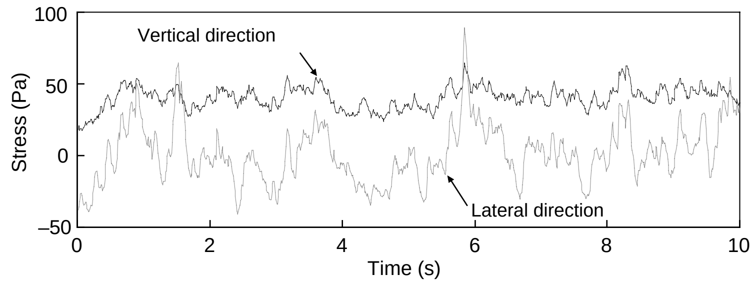

Figure 7 Variation of shear and drag stress working on the membrane surface at the bottom part

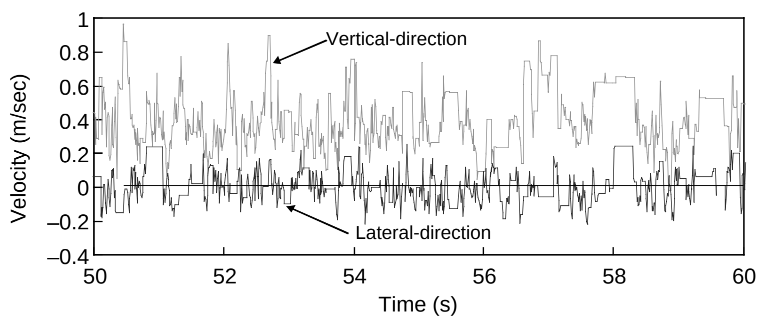

Figure 8 Variation of velocity measured near the bottom part of the membrane module

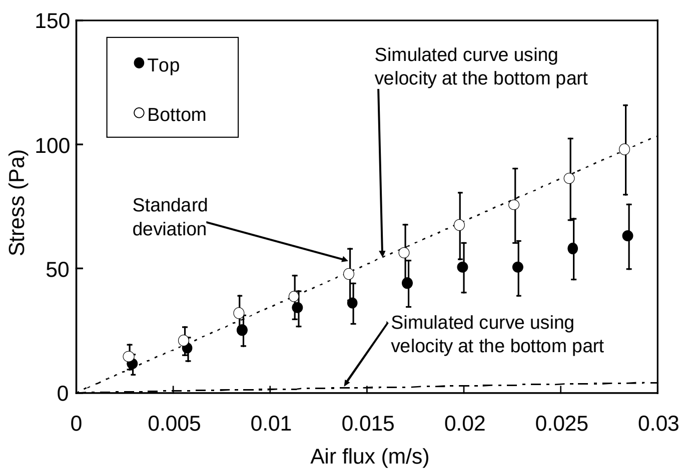

Figure 9 Comparison of measured and simulated time-averaged drag stress on hollow fibre

where $\bar{\tau}$: time-averaged shear stress, ρ: water density, C_D: drag-force coefficient for a cylinder (= 1.2), $\bar{v}$: time-averaged upward water velocity. It is shown that drag stress on bottom part hollow fibre membrane is explained well by drag force by water velocity while drag force at top part of the membrane module, where bubble flow does not directly hit the membrane, cannot be explained by water velocity thereby implying importance of the interaction with bubbles.

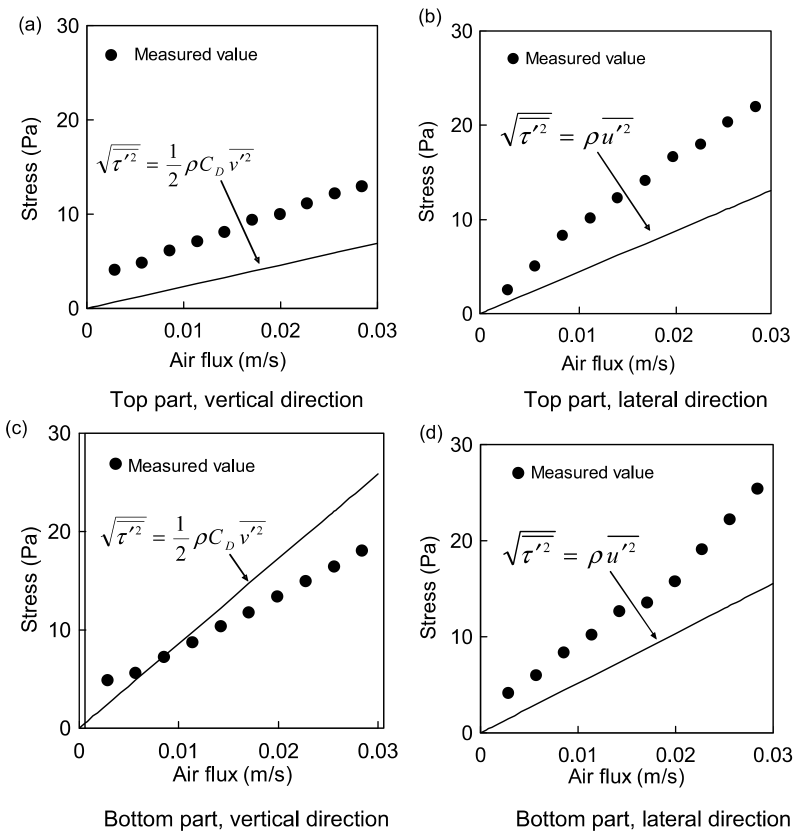

Figure 10 Comparison of measured and simulated standard deviation of stress on hollow fibre

Because variation of stress on the membrane surface shows very intense fluctuation, the mechanism of the production of the stress variation was discussed using the following models;

(Vertical direction) $$\sqrt{\overline{\tau'^2}} = \frac{1}{2}\rho C_D \overline{v'^2} \tag{5}$$

(Lateral direction) $$\sqrt{\overline{\tau'^2}} = \overline{\rho u^2} \tag{6}$$

where $\sqrt{\overline{\tau'^2}}$: rms (root-mean-square) of stress variation, v': vertical-direction velocity fluctuation, u':lateral-direction velocity fluctuation. Figure 10 shows comparison of measured and simulated standard deviation of stress on hollow fibre. Although the measured and the simulated rms values of stress on hollow fibre are not in complete agreement, both of the values are of the same order and it is suggested that fluctuation of stress on hollow fibre is caused by strong velocity fluctuation induced by bubble flow.

Conclusions

Shear stress on hollow fibre membrane surfaces caused by aeration was measured directly using a two-direction load sensor. In a vertically-set membrane module, time-series data of upward-direction shear stress showed intense fluctuation, which was caused by turbulent flow around the hollow fibre and also by the effect of interaction between bubbles and the membrane surface. Time-averaged upward-direction shear stress value was compared to theoretical shear stress values considering the effect of water flow on the membrane surface. Measured time-average shear stress values were almost 200 times larger than theoretical values suggesting that strong interactions between bubbles and solid surface are the major mechanism of shear stress working on hollow fibres.

In a laterally-set membrane module, the bottom part of the membrane, where bubble flow directly hits the surface, upward-direction (vertical direction) drag force is caused by water velocity while drag force at the top part of the membrane, where bubble flow does not hit the surface directly, is influenced by the interaction with bubbles. Shear and drag stress on the membrane surface shows strong fluctuation that is caused by fluctuation of velocity of bubble flow.

References

Laborie, S., Cabassud, C., Durand-Bourlied, N. and Lainé, J.M. (1998). Fouling control by air sparging inside hollow fiber membranes effects on energy consumption. *Desalination.*, **118**, 187–196.

Le-Clech, P., Alvarez-Vazquez, H., Jefferson, B. and Judd, S. (2003). Fluid hydrodynamics in submerged and sidestream membrane bioreactors. *Water Science and Technology*, **48**(3), 113–119.

Moursali, E., Marié, J.L. and Bataille, J. (1994). An upward turbulent bubbly boundary layer along a vertical flat plate. *Int. J. Multiphase Flow.*, **21**(1), 107–117.

Nagaoka, H., Tanaka, A. and Miyamoto, Y. (2001). *Measurement of Aeration-Induced Shear Stress Acting on Flat-Sheet Membrane in Submerged-Type Membrane Bioreactor*. Asian Waterqual 2001, First IWA Asia-Pacific Regional Conference, Proceedings I, 171–176, 2001

Nagaoka, H., Tanaka, A. and Toriizuka, Y. (2003). Measurement of effective shear stress working on flat-sheet membrane by air-scrabbling. *Water Science and Technology: Water Supply*, **3**(5–6), 423–428.

Nakoryakov, V.E., Kashinsky, O.N., Randin, V.V. and Timkin, L.S. (1996). Gas-liquid bubbly flow in vertical pipes. *Trans. ASME J. Fluids Eng.*, **118**, 377–382.

Oba, K. (1985). *Study on Microstructure in Air-Water Bubbly Flow by Laser Doppler Measurement*. Proc. 4th Multiflow symposium –multiphase flow characteristics and measurement-, pp. 45–67 (in Japanese).

Ozaki, N. and Yamamoto, K. (2001). Hydraulic effects on sludge accumulation on membrane surface in crossflow filtration. *Water Research*, **35**(13), 3137–3146.