Estimation of shear stress working on submerged vertically set hollow fibre membrane in MBRs

Tairi Li, H. Nagaoka, T. Itonaga and Y. Nakahara

ABSTRACT

This study is aimed at elucidating the mechanism by which rising air bubbles induce shear stress on the surface of hollow fibre membranes in submerged membrane bioreactors (MBRs). Shear stress working on vertically set hollow fibre membrane surfaces caused by aeration was measured directly using a two-direction load sensor connected to one hollow fibre at the centre of the 'vegetation' of the module and was found to be in a downward direction suggesting the existence of strong downward flow at the lower part of the module caused by eddies behind the pod. Velocity profile inside the membrane module was measured using a laser Doppler velocimeter showing slow upward direction flow inside the module which was caused by the influence of the hollow fibre vegetation. Just one hollow fibre was vertically set free in the bubble flow to measure shear stress on the fibre. A computational fluid dynamics (CFD) method was employed to numerically calculate the shear stress suggesting the effectiveness of CFD for the evaluation of shear stress on hollow fibre membrane.

Key words | bubble flow, CFD, hollow fibre, laser Doppler velocimeter, shear stress, SMBR

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INTRODUCTION

As a wastewater treatment technology, the membrane bioreactor (MBR) process, which is the combination of membrane separation and activated sludge process, has gained considerable attention because of its potential advantages over those of conventional biological treatment processes. In comparison with the standard activated sludge system, the MBRs have merits such as complete removal of solids from an effluent, better nutrient and organic removal efficiency, higher organic loading rate and smaller footprint requirement.

The submerged membrane bioreactor (SMBR) is a membrane bioreactor system with membrane modules submerged in an aeration tank, the permeate of which is sucked out of the aeration tank (Yamamoto *et al.* 1989). It requires no circulation pumps which are necessary for side-stream MBRs thereby making it an energy conserving system.

In the submerged membrane bioreactors, aeration plays a major role in the cleaning of the membrane surface. Air supply rate is therefore a critical factor in determining membrane fouling rate. Shear stress on the membrane can be controlled by air flow rate. A higher air flow rate can maintain the reactor with longer chemical cleaning intervals. However, higher air flow supply would result in a higher electricity consumption rate. It is therefore very important to know how air flow rate influences the magnitude of the shear stress on the membrane surface.

Several studies have been conducted concerning the interaction between bubble flow and a membrane surface. Ozaki & Yamamoto (2001) studied the hydraulic effects on sludge accumulation on a membrane surface in crossflow filtration and suggested the importance of shear stress on the membrane surface. Nagaoka *et al.* (2003) measured shear stress directly 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

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membranes to maintain stable permeate flux. Nagaoka *et al.* (2006) measured directly drag-force and shear stress working on a submerged laterally set hollow fibre membrane. Water velocity in bubble flow was also measured using a laser Doppler velocimeter revealing that the drag force working on the membrane surface was closely related to upward-direction water velocity.

However, very little research has been conducted concerning shear stress on vertically set hollow fibres in submerged MBRs. This research is aimed at elucidating the mechanism of the induction of the shear stress on hollow fibres and developing a method to estimate shear stress on submerged hollow fibres utilising a computational fluid dynamics (CFD) method.

MATERIALS AND METHODS

Evaluation of shear stress on a hollow fibre at the centre of the module

Figure 1 shows a schematic diagram of an experimental set-up used for measuring shear stress working on a vertically set hollow fibre membrane module induced by bubble flow (aeration). A polyvinylidene difluoride (PVDF) microfiltration hollow fibre membrane (outer diameter: 2.8 mm length: 900 mm) was set vertically in a tank filled with tap water. A single hollow fibre positioned at the centre of the module was connected to a two-direction loads sensor (SSK Co. Ltd, Japan: LV30-1, range: 0.1 kgf) at the bottom end in order to evaluate the influence of hollow fibre vegetation inside the membrane module on forces working on the membrane. Two air diffusers (a schematic diagram of the diffuser is shown in Figure 3) were set at 325 mm below the sensor so that air ejected from the diffuser touches the hollow fibres effectively. Air flow rate was varied between 6.0 and 22 l $\min^{-1}$.

The load sensor could measure total force working to the single hollow fibre caused by bubble flow around the membrane module. Measured forces (vertical and lateral directions) were divided by total surface area of the membrane to calculate vertical-direction shear stress and lateral-direction drag force working on the membrane.

Output from the load sensor was stored in a personal computer through an A/D converter to obtain time-series

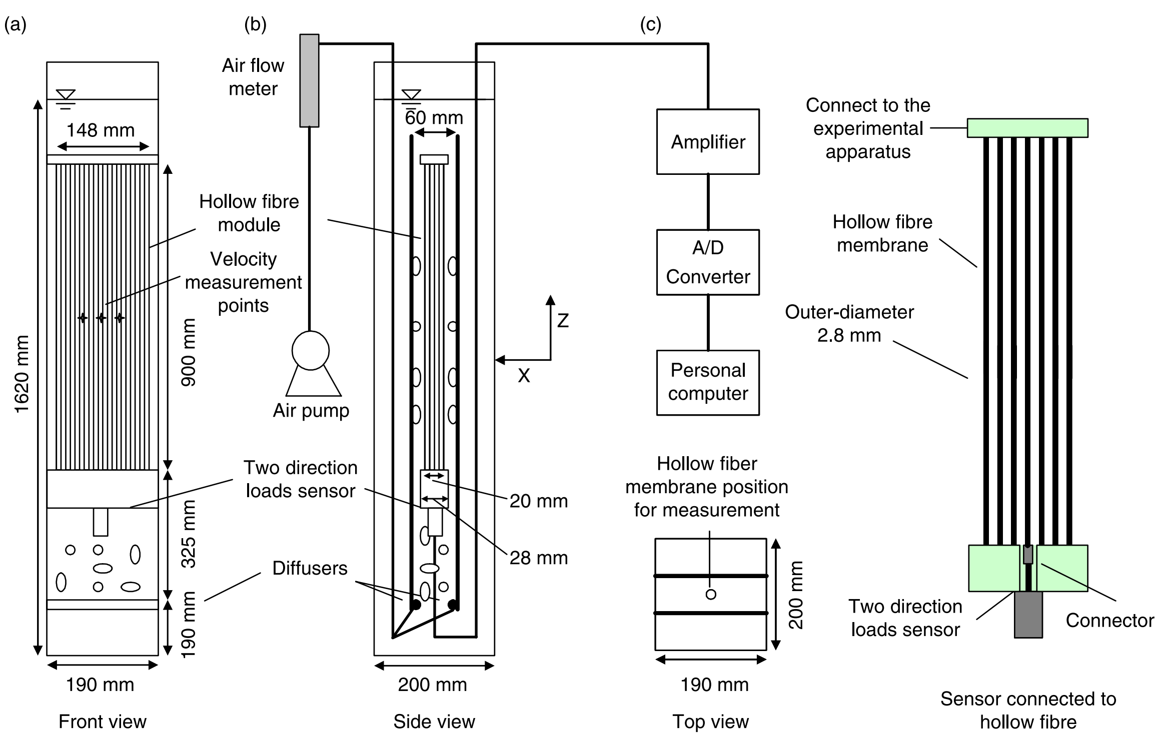

Figure 1 | Schematic diagram of an experimental set-up used for measuring shear stress on a vertically set hollow fibre module induced by bubble flow.

data. Calibration of the sensor was conducted before every measurement under a zero-shear stress condition stopping the supply of air.

The velocity profile of bubble flow inside and outside the 'membrane module vegetation' was directly measured using a laser Doppler velocimeter at 940 mm above the bottom of the tank. Ensemble-averaged profiles were calculated from measurement data at three positions as shown in Figure 1. Sampling number and sampling frequency was 4,096 and 100 Hz, respectively.

Evaluation of shear stress on a vertically set hollow fibre by experiment

In order to gather basic information on the relationship between shear stress on a hollow fibre membrane and velocity around the membrane, an experiment using only a single hollow fibre positioned in the bubble flow was conducted. Figure 2 shows a schematic diagram of an experimental set-up for measuring shear stress working on a vertically set hollow fibre membrane induced by bubble flow without any interactions with neighbouring fibres. A single hollow fibre (the same hollow fibre as was used in the previous experiment; Figure 1) was submerged in the tank instead of the hollow fibre membrane module.

The bottom end of the single hollow fibre was replaced with a guitar string in order to minimize the influence of strong eddies produced at the bottom and to allow correct measurement measure correctly (existence of the eddies was found in the experiment using the membrane module and will be explained below). Other equipment such as the load sensor and a diffuser as in Figures 1 and 2 were the same, as shown in Figure 3.

Velocity profiles of bubble flow were also directly measured using a laser Doppler velocimeter at 1,100 mm from the bottom at three different positions as shown in Figure 2 in order to calculate ensemble-averaged velocity profiles. Sampling number and sampling time were 6,144 and 61.44 s, respectively.

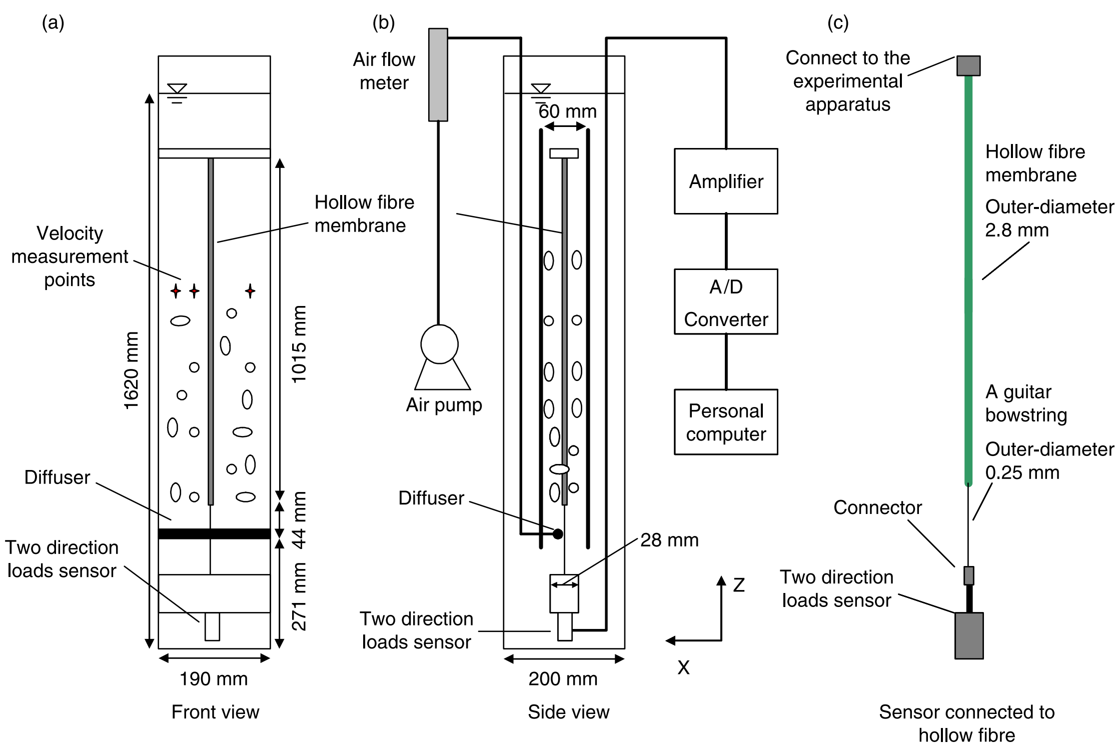

Figure 2 | Schematic diagram of an experimental set-up used for measuring shear stress on a vertically set one hollow fibre induced by bubble flow.

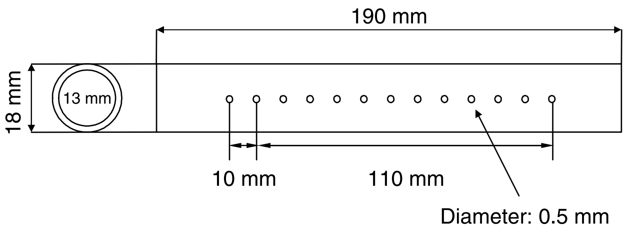

Figure 3 | Schematic diagram of diffuser (13 orifices).

Calculation of shear stress working on a single hollow fibre using CFD

In order to verify the usefulness of CFD in evaluating shear stress working on the hollow fibre membrane surface, a numerical simulation using a two-phase hydrodynamics model was conducted to calculate shear stress and was compared with measured shear stress values using the single-fibre experimental set-up (Figure 2). A commercial CFD code (ANSYS-CFX11.0) was employed to simulate two-phase flow with the Eulerian-Eulerian approach. In order to consider the momentum transfer between the continuous liquid phase and the dispersed gas phase, the Grace Drag Model was used to include the effect of bubble deformation and gas hold-up on the resistance coefficient. For simplification, bubble size was assumed to be uniform at 5 mm. The single hollow fibre membrane was regarded as a single thin cylinder.

Steady-state three-dimensional calculation was conducted on a hexahedral mesh with approximately 870,000 cells. Degassing condition was set on the top of the reactor. For the modelling of turbulence in the liquid phase, the shear stress transfer (SST) model was used, while the zero-equation model was used for the calculation of the gas phase.

RESULTS AND DISCUSSION

Shear stress working on a hollow fibre membrane set inside the membrane module

Figure 4 shows an example of time-series stress data. Lateral (X)-direction stress (drag stress) showed strong fluctuation, the intensity of which was about 3 ~ 4 times larger than that of the vertical (Z)-direction suggesting strong interactions with neighbouring fibres and existence of strong turbulent eddies inside the module. This value should ideally be distributed around zero because the sensor was set symmetrically. However because of a slight difference between air flow rates from the two air diffusers set around the module, irregular flow was induced near the sensor thereby causing the non-zero value of X-direction shear stress. Vertical (Z)-direction stress shows small minus values, indicating downward direction shear stress.

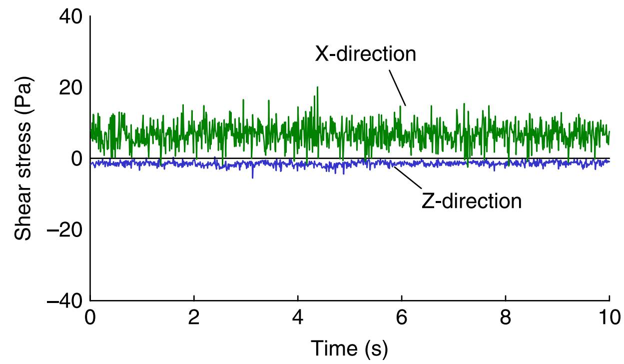

Figure 4 | Variation of shear and drag stress working on a hollow fibre at the centre of the membrane module (air flow rate: 22 l min^{-1}).

Figure 5 shows an example of time-series velocity data. Vertical (Z)-direction velocity shows strong fluctuations, suggesting the existence of intense turbulence in the bubble flow outside the module, which might be the reason for the strong fluctuation of X-direction stress as shown in Figure 4. Lateral (not X)-direction velocity variation shows many plateaus, caused by the blocking effect of laser beams by bubbles.

Figure 6 shows the relationship between air flow rate and time-averaged vertical (Z)-direction shear stress with the standard deviation of fluctuation expressed by the

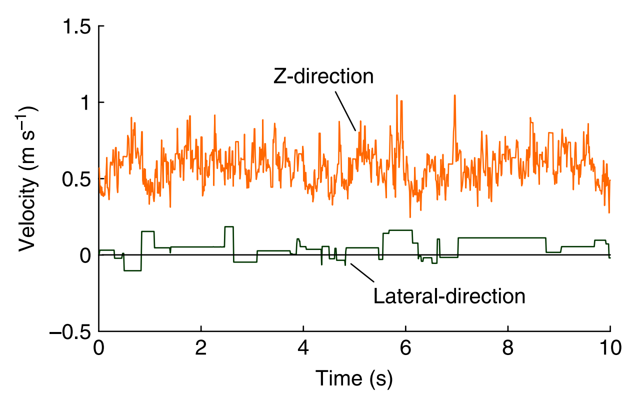

Figure 5 | Variation of velocity measured outside the membrane module (4 mm from the wall, air flow rate: 6 l min^{-1}).

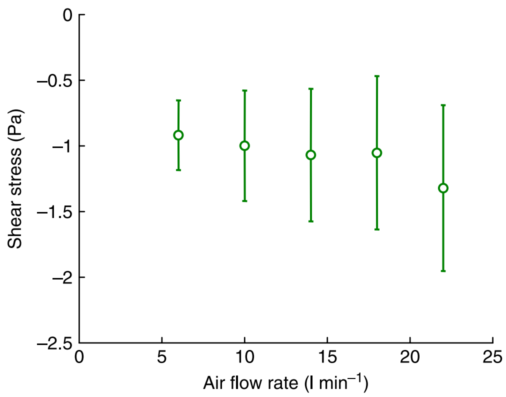

Figure 6 | Relationship between air flow rate and time-averaged vertical (Z)-direction shear stress on the membrane surface with standard deviation expressed by the length of bars.

length of bars. Probably because of the strong downward direction flow produced around the bottom part of the membrane module, the shear stress shows minus (downward direction) values. The figure also shows that, with the increase of air flow rate, downward-direction shear stress (absolute values in Figure 6) and standard deviation (fluctuation) increase, suggesting the effect of bubbles as an inducer of stronger turbulence.

Flow inside and outside the hollow fibre membrane module

Figure 7 shows examples of velocity profiles inside and outside the membrane modules. For the modelling of the profiles, Equation (1), which was proposed by Yamada & Kawabata (1982*a*,*b*) for the modelling of seepage flow in a porous riverbed, was employed:

$$v = v_0 + v_s \cdot \exp(-k \cdot z) \quad (1)$$

where v is time and ensemble-averaged upward water velocity (m s^{-1}), v_0 the convergence value of velocity (m s^{-1}), v_s time and ensemble-averaged upward water velocity near the hollow fibre module surface (m s^{-1}), k penetration coefficient (1 mm^{-1}), and z is distance from the hollow fibre module surface (mm).

Because it is very difficult to measure velocity right at the centre of the membrane module owing to the shadow effect of fibres, regression curves from Equation (1) were extrapolated to the centre of the module to calculate time-averaged velocity there.

Figure 8 shows the relationship between air flow rate and estimated time-averaged vertical-direction velocity at the centre of the module.

Considering the results of Figure 6 and Figure 8, it is suggested that strong downward-direction flow at the centre of the module somewhere between the sensor and the velocity measurement points should exist to cancel upward-direction velocity at the upper region of the module, the concept of which is shown in Figure 9. Because flow inside the hollow fibre membrane module is influenced by the density of fibres, air flow rate and hollow fibre density are key parameters to determine shear stress on the hollow fibre module.

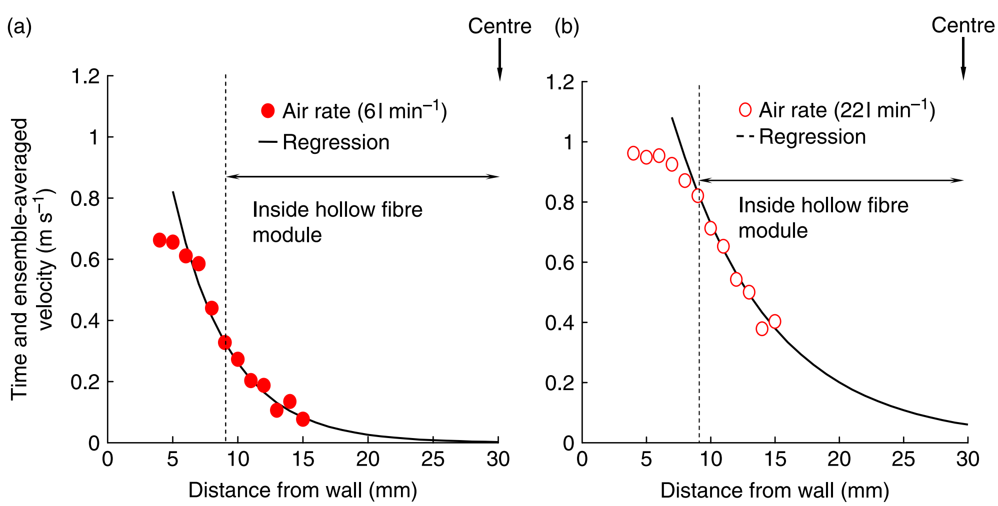

Figure 7 | Time-averaged velocity distribution inside the hollow fibre module.

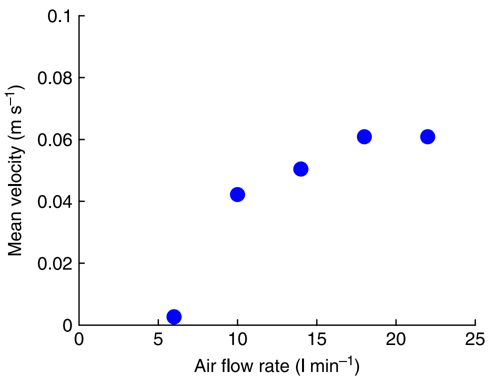

Figure 8 | Estimated time-averaged vertical-direction velocity at the centre of the hollow fibre module.

Evaluation of shear stress working on a single hollow fibre membrane by experiment and CFD simulation

Figure 10 shows an example of a velocity field around the single hollow fibre calculated by CFD. From velocity profiles near the hollow fibre, shear stresses on the membrane surface can be calculated over the whole surface area. By integrating shear stress over all the areas, averaged shear stress was obtained.

Figure 11 shows a comparison of simulated and measured values of shear stress on the hollow fibre surface. When the air flow rate is less than $20\,\mathrm{l\,min^{-1}}$, both values are in good agreement, suggesting the effectiveness of CFD for the evaluation of shear stress on a hollow fibre membrane. However, when the air flow rate is greater than $20\,\mathrm{l\,min^{-1}}$, measured values are larger than simulated values, probably as a result of the effect of the waving motion of the fibre, which would work to add drag force. This effect should be considered for the simulation of shear stress when fibres are waving in bubble flow.

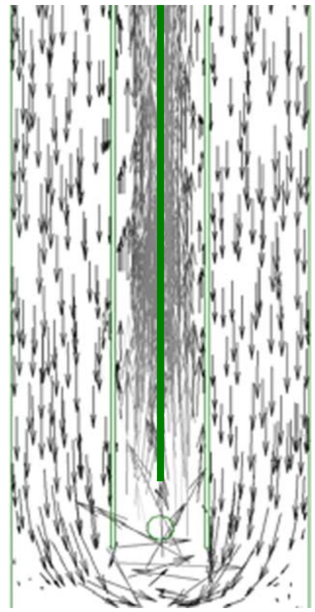

Figure 10 | Example of CFD simulation of flow around a single hollow fibre in bubble flow.

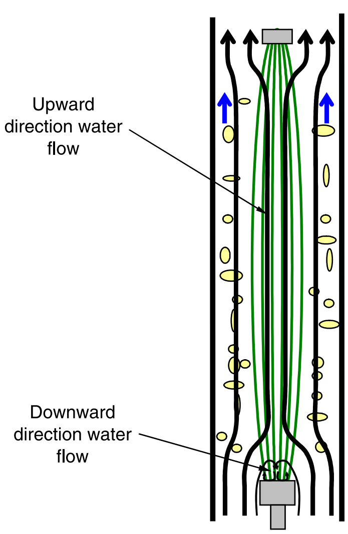

Figure 9 | Image of water flow inside the membrane module induced by bubble flow (side view).

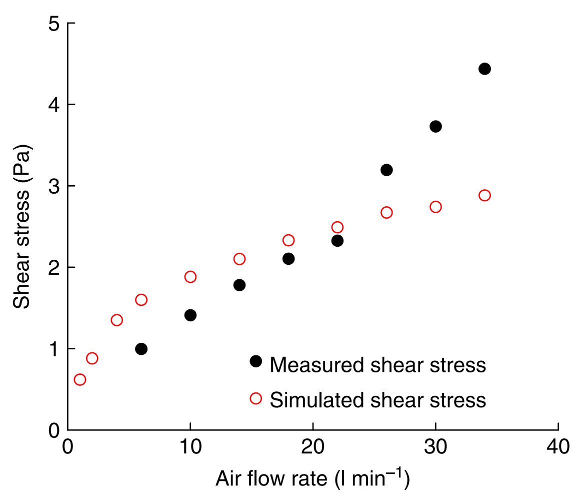

Figure 11 | Comparison of simulated shear stress and measured time-averaged shear stress.

CONCLUSIONS

Shear stress working on a vertically set submerged hollow fibre membrane module in bubble flow was measured directly using a two-direction load sensor with velocity measured by a laser Doppler velocimeter. At the centre of the module, shear stress showed a downward direction, probably owing to strong eddies inside the module. Velocity profiles inside the module were found to be influenced by the density of the hollow fibre.

By comparing measured shear stress working on one hollow fibre with simulated values calculated by a CFD method, it was concluded that CFD can be an effective tool for the estimation of shear stress on hollow fibre. However, consideration of waving motions of fibres and velocity profiles inside membrane modules would be necessary for more accurate estimation of shear stress.

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