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Experimental assessment of filtration of biomass with transverse and axial fibres

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Abstract

The orientation of hollow fibres (vertical or transversal) is of interest for the design of submerged hollow fibre modules. The purpose of this paper is to assess the effect of fibre orientation on performance for the filtration of biomass. A crossflow fibre cell was built to hold hollow fibres in well-controlled transverse or axial orientation. Two sizes of polypropylene hollow fibre, 0.65 and 2.7 mm (o.d.) were tested. A microscope and video-camera system was used to monitor particle deposition on the fibres. Filtration experiments with and without bubbling were carried out using yeast as model particles. The experiments showed that the effect of fibre orientation on the filtration process depends on the system conditions (with or without bubbling, fibre diameter, etc.). For filtration without bubbling, the transverse flow resulted in about 50% enhancement in filtration performance for 0.65 mm fibres but the benefits was insignificant for 2.7 mm fibres. The different filtration behaviour between 0.65 and 2.7 mm fibres in the filtration of biomass with transverse flow was attributed to the effect of wall shear around the transverse fibres, fibre movement, vortex formation, and inertial impaction. On the other hand, for filtration with bubbling, around 5–15% lower flux declines occurred with axial orientation for both 0.65 and 2.7 mm fibres. Comparing the results obtained with and without bubbling, the effect of fibre orientation on filtration with the smaller fibre decreased with injection of air. This implies that for filtration with bubbling the process tends to be dominated by the turbulence caused by the two-phase flow. However, axial bubble flow, rather than transverse does promise better performance in the membrane filtration of biomass.

Keywords: Fibre membrane; Fibre orientation; Microfiltration; Design; Bubbling

1. Introduction

Directly submerging hollow fibres membranes into a wastewater bioreactor has become a new concept for wastewater treatment [1–3]. In this type of membrane-based bioreactor system, the activated sludge is retained outside the hollow fibres and the process effluent is removed out of the lumen by suction or gravity. The performance of the membrane separation tends to be limited by membrane fouling which is influenced by operational conditions and the design of the system. For the operation of the submerged system, controlling imposed flux level (usually in the range of 10–20 l/m^2 hr) and injecting air into the fibre bundle are the main techniques to control particle deposition on the hollow fibres [4–6]. For the design of the submerged module, fibre orientation is one of the main issues to be considered.

For the hollow fibre submerged module, the fibre can be positioned in two different ways: vertically and horizontally. With the vertical arrangement, bubbles rise along the fibre and a two-phase flow forms in the axial direction of the fibre bundle. In contrast, with the transverse arrangement, the two-phase flow caused by bubbling impacts the fibre perpendicularly. Hydrodynamic studies of the flow around a cylinder suggested that the transverse arrangement could disturb the flow streams and cause turbulence around the cylinder [7]. Although the turbulence caused by transverse flow has been confirmed to be beneficial for reverse osmosis and ultrafiltration of molecular solutions [8,9], an assessment of fibre orientation on the filtration of biomass has not been reported. The difference between filtration of molecular solutions and particle suspensions with transverse flow is that dissolved molecules will strictly follow the fluid streamlines, but the relatively large biomass particles may fail to follow a rapidly curving flow streamline around transverse fibres due to their inertia. This inertial deviation of particles from the streamline may result in increased deposition on some locations of the fibres under some conditions.

The work presented aims to understand the effect of fibre orientation on filtration of biomass without and with bubbling. In the experiments, fibres of 2.7 and 0.65 mm outer diameter were tested using yeast as model particles. The

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effect of fibre orientation, crossflow velocity, and fibre diameter were investigated. A comparison between axial and transverse orientation was made for filtration with and without bubbling. In addition, a microscope/video-camera system was used to observe the flow around the transverse fibres and monitor particle deposition on the fibres. The observations confirmed the effect of inertial impaction on filtration of biomass with transverse flow under certain experimental conditions.

2. Experimental equipment and materials

Fig. 1 shows the crossflow cell used in the experiments, which consists of a bottom part, top part, and support frame which provides a 190 mm × 48 mm × 4 mm flow channel. Fibres can be fixed axially or transversely in the support frame as shown in the figure. The window in the top part of the cell allows observation of flow around the fibres and monitoring of particle deposition on fibres using a Zeiss light microscope (Axiolab Zeiss) and video-camera (WU-BP 310, Panasonic). For the observation, the objective lens of the microscope was adjusted to focus on the outer edge of the fibre as shown in Fig. 1.

Crossflow and airlift systems (Fig. 2) were used for filtration experiments. Fig. 2a depicts the crossflow system used in the experiments. The crossflow rate was controlled by a gear pump (2) (P/N 74011-41, S/N 470849, Cole-Parmer). The flow rates of feed and air from a pressurised cylinder were measured by rotameters (3) and (4). Air was injected into the cell from a porous plate fixed on the bottom part. Fig. 2b shows the airlift system used where the hollow fibres were submerged in the feed. When air was injected into the cell, an up-flow occurred due to the difference between the weight of the air-feed mixture in the cell (riser) and weight of feed in the tank.

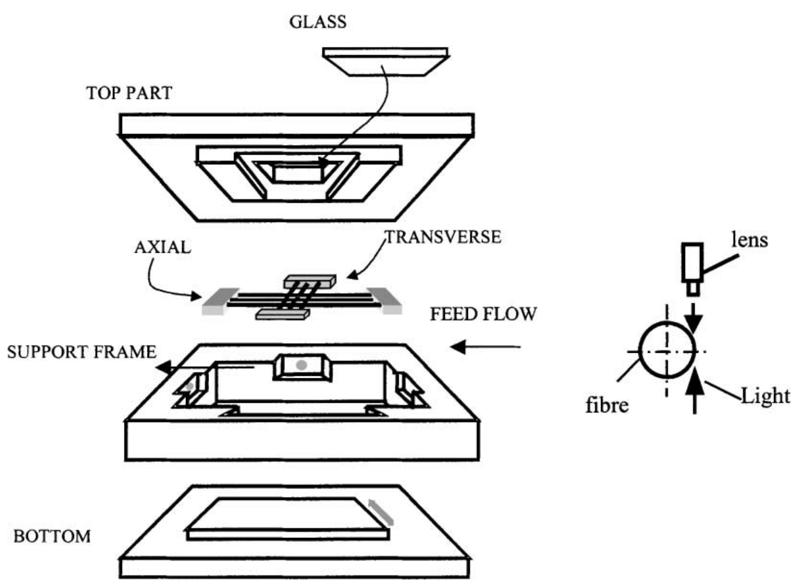

Fig. 1. Schematics of the crossflow cell.

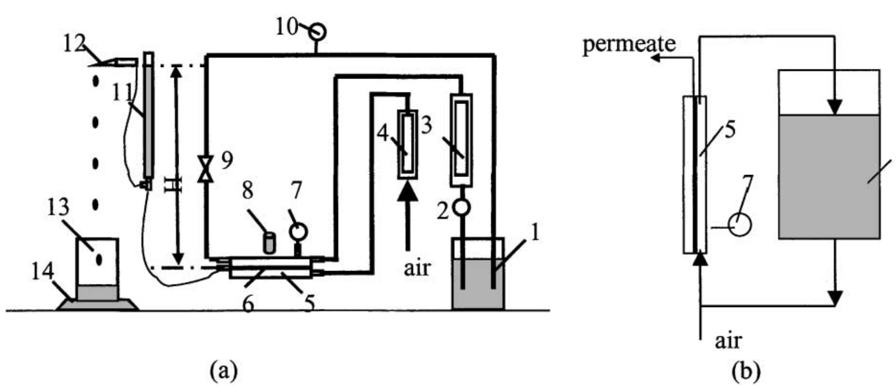

Fig. 2. Schematics of the experimental set-up: (a) crossflow system, (b) submerged system. (1) Feed tank, (2) pump, (3) liquid flowmeter, (4) gas flowmeter, (5) crossflow cell, (6) hollow fibre, (7) pressure gauge, (8) microscope/video system, (9) valves, (10) pressure gauge, (11) glass tube, (12) permeate overflow outlet, (13) permeate collector, (14) balance.

All of the experiments were carried out with the initial flux controlled by adjusting the pressure on the feed side and the height (H) of the overflow of the permeate. The flux has been calculated based on the average diameter of the fibres. The performance was evaluated by comparing the flux decline (D_J) in filtration and performance enhancement (E_{D_J}).

The flux decline is defined as

$$D_J = 100 \times \frac{\text{initial flux} - \text{final flux}}{\text{initial flux}} \quad (1)$$

and performance enhancement is defined as

$$E_{D_J} = \frac{100 \times (D_{J1} - D_{J2})}{D_{J1}} \quad (2)$$

where 1 and 2 are the conditions compared.

Dry yeast having a mean diameter 5 μm was used as the model particle. The membranes were 0.2 μm polypropylene hollow fibres with outer diameters of 2.7 mm (AKZO) and 0.65 mm (US-Filter) and inner diameters of 1.8 and 0.39 mm, respectively.

3. Experimental results

3.1. Filtration without bubbling

3.1.1. Filtration with 0.65 mm fibres

Fig. 3 shows the flux decline for 90 min filtration of yeast suspension with 0.65 mm transverse and axial fibres at different crossflow velocities. The axial module included a four-fibre bundle and the transverse module included four four-fibre bundles between which the spacing was 20 mm. In the experiments, the initial flux was set at a similar level (Table 1). From the figure, we can see that for both axial and transverse fibres, the flux decline decreased with the increased in crossflow velocity. However, the sensitivity to increasing crossflow velocity for axial and transverse fibres was different (Fig. 4). When the crossflow velocity increased from 0.09 to 0.43 m/s, the decrease in flux decline for transverse fibres (E_{D_J}) was about 50%, while it was only about 27% for axial fibres. This indicates that for 0.65 mm fibres, the transverse fibres were more sensitive to the increase in crossflow velocity.

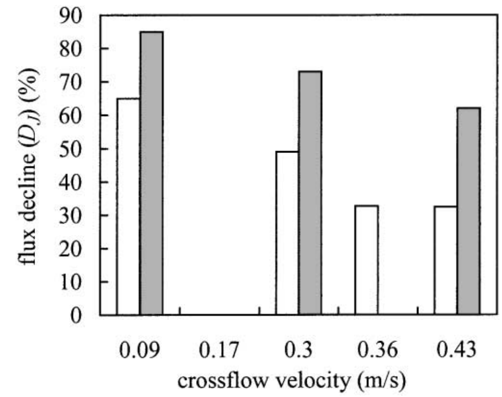

Fig. 3. Flux decline for 90 min filtration of 5 g/l yeast suspension with 0.65 mm axial and transverse fibres at different crossflow velocities (without bubbling): (□), transverse; (■), axial.

Comparing flux decline in Fig. 3 with axial and transverse fibre, we can see that the flux decline with the transverse fibres was considerably lower than that with the axial positions at the same crossflow velocity. For the 0.65 mm fibres, the maximum performance enhancement by transverse flow was more than 50% (at 0.3 m/s crossflow velocity) (Fig. 5). These results indicate that for 0.65 mm fibres transverse flow was superior to the axial in filtration without bubbling.

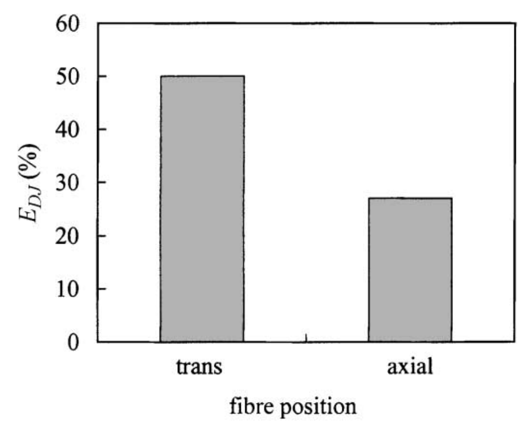

Fig. 4. Performance enhancement in filtration with axial and transverse fibres by increasing crossflow velocity from 0.09 to 0.43 m/s (without bubbling). $E_{D_J} = 100 \times (D_{J0.09} - D_{J0.43})/D_{J0.09}$.

Table 1
Initial fluxes (l/m^2 h) related to the experiments in Figs. 3, 6 and 7

Crossflow velocity (m/s)	Fig. 3		Fig. 6		Fig. 7	
	Transverse	Axial	Spacing 5 (mm)	Spacing 20 (mm)	Transverse	Axial
0.09	97	99	–	94	–	–
0.17	–	–	102	94	94	102
0.3	97	102	102	117	117	112
0.36	95	–	–	–	–	–
0.43	93	86	86	83	83	85

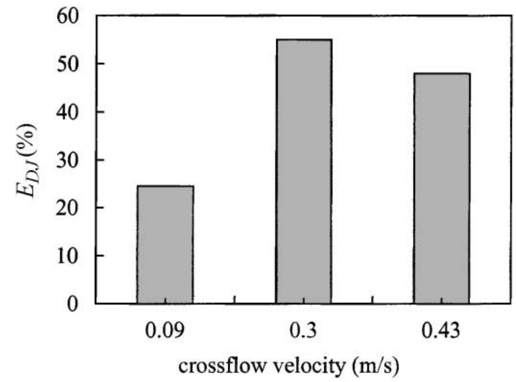

Fig. 5. Comparison between axial and transverse fibre at different crossflow velocities for filtration with 0.65 mm fibres (without bubbling). $E_{D_J} = 100 \times (D_{J\text{axial}} - D_{J\text{trans}})/D_{J\text{axial}}$.

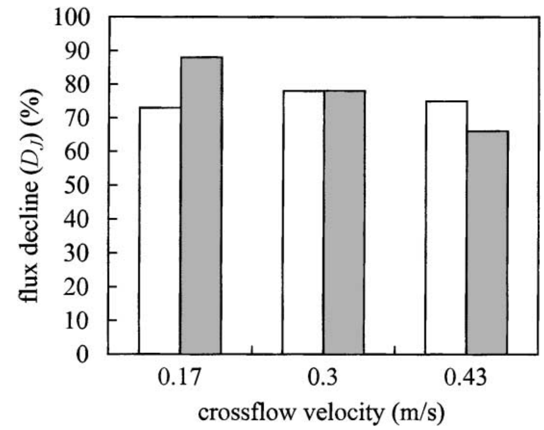

Fig. 7. Comparison between axial and transverse flow in filtration of 5 g/l yeast with 2.7 mm fibres (without bubbling): (□), transverse; (■), axial.

3.1.2. *Filtration with 2.7 mm fibres*

Fig. 6 shows the flux decline for 90 min filtration with two 2.7 mm transverse fibres. The inter-fibre spacings tested, which was defined as the distance between the axis of the fibres, were 5 and 20 mm. Table 1 shows the initial fluxes related to the experiments. From the figure, we can see that for the 2.7 mm fibres, the performance was insensitive to the increase in crossflow velocity in the range tested. This is quite different from that observed in filtration with the 0.65 mm fibres (Fig. 3).

Fig. 7 compares the flux decline in filtration with the transverse fibres with a single axial fibre at different crossflow velocities. From the figure, we can see that for the relatively low crossflow velocity (0.17 m/s), the flux decline with the transverse fibres was slightly lower than that with axial fibres. However, since the filtration with the transverse fibre was insensitive to the increase in crossflow velocity, the axial fibres became better at 0.43 m/s crossflow velocity. A higher crossflow velocity was not tested here due to the limitation of the capacity of the pump. A longer experiment with single axial and transverse fibres was carried out to make a further assessment of the effect of fibre orientation. Fig. 8 shows the flux time curves for 6 h filtration at 0.4 m/s crossflow velocity. The experiment indicated that the final flux after 390 min of filtration with the axial fibre was about 30% higher than that obtained with the transverse fibre. An assessment of membrane resistance after filtration and water rinsing also showed that the increase in membrane resistance was 23.6% higher with the transverse fibre than that with the axial fibre.

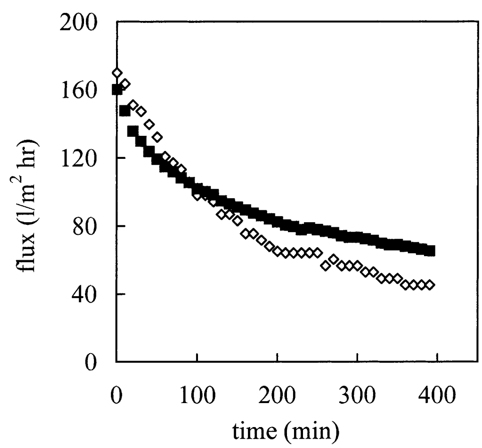

Fig. 8. Flux–time curve in filtration of 0.1 g/l yeast suspension with a single axial and transversal fibre (without bubbling). Velocity, $u = 0.4$ m/s: (◇), transverse; (■), axial.

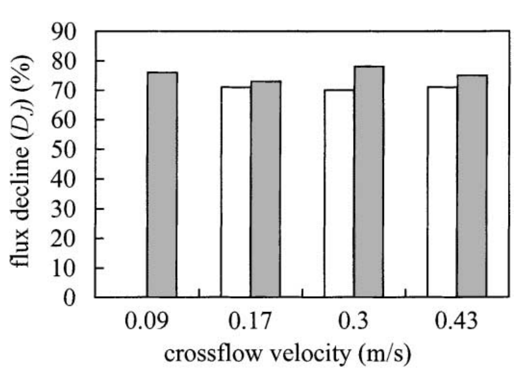

Fig. 6. Effect of crossflow velocity in filtration of 5 g/l yeast with 2.7 mm transverse fibres: (□), spacing 5; (■), spacing 20.

3.1.3. *Comparison between 0.65 and 2.7 mm fibres*

Comparing the results obtained with 0.65 and 2.7 mm fibres, it can be seen that filtration behaviour with the transverse flow can be considerably affected by the fibre diameter. Fig. 9 shows the difference in flux declines, plotted as ‘performance enhancement’ (Eq. (2)), for filtration with 0.65 and 2.7 mm fibres at different crossflow velocities. From this figure, we can see that for both transverse and axial orientation, lower flux declines were observed with the smaller fibres, but the difference between the small and large fibre was much more significant in filtration with transverse flow.

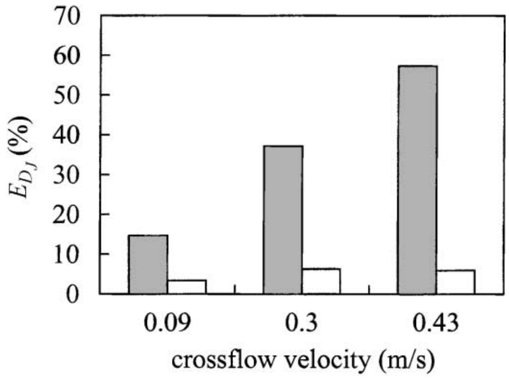

Fig. 9. Comparison between 0.65 and 2.7 mm fibres in filtration of 5 g/l yeast with axial and transverse orientation (without bubbling). $E_{D_J} = 100 \times (D_{J2.7} - D_{J0.65})/D_{J2.7}$: (□), axial; (■), transverse.

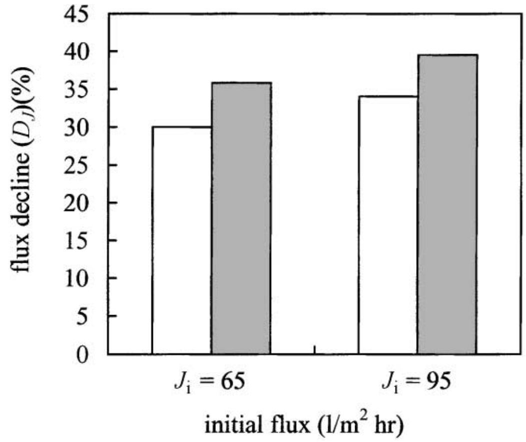

Fig. 10. Comparison between axial and transverse flow in filtration with 0.65 mm fibres with bubbling: (□), axial; (■), transverse.

The benefit of transverse flow for the small fibre increased with increase in crossflow velocity. At 0.43 m/s crossflow velocity, the flux decline with the 2.7 mm fibres was more than 50% higher than that with the 0.65 mm fibres.

3.2. Filtration with bubbling

For the submerged system, bubbling is used to control particle deposition on hollow fibres. In order to assess the effect of fibre orientation on performance of filtration with two-phase flow, filtration experiments with bubbling were carried out with the different fibre positions. Fig. 10 shows the results for filtration with bubbling using the 0.65 mm fibre module mentioned in Section 3.1. In these experiments, the simulated submerged system (Fig. 2b) was used and the superficial velocity of gas was set at 0.2 m/s. From the figure, we can see that the flux decline with axial orientation is lower than that with transverse fibres. For 2.7 mm fibres, 5–15% lower flux decline with axial orientation has previously been reported for different gas flow rates [10].

The difference in flux decline between 2.7 and 0.65 mm axial fibres for filtration without bubbling was not very significant (<10%) (Fig. 9), but the difference between these two fibres in axial orientation was found to increase considerably with the injection of the air. Table 2 shows the results obtained in filtration with 2.7 and 0.65 mm axial fibres with and without bubbling. From this table, we can see that a significant lower flux decline occurred for filtration with 0.65 mm fibre with bubbling. A further assessment on the effect of fibres diameter for filtration with axial fibre has been discussed elsewhere [11].

4. Discussion

4.1. Filtration without bubbling

For filtration without bubbling, the experimental results presented highlight the difference in filtration behaviour between 0.65 and 2.7 mm fibres in transverse flow. For 0.65 mm fibres, the transverse was much better than axial and the benefit of the transverse increased with the increase in crossflow velocity. For 2.7 mm fibres, the performance of filtration with transverse flow was insensitive to the increase in crossflow velocity in the range tested so that axial became better than transverse at a relatively high crossflow velocity (0.43 m/s). Comparing the flux decline with these two fibres under the same filtration conditions, the 0.65 mm fibre was much better than the 2.7 mm fibre in filtration with transverse flow.

For filtration of biomass with transverse flow, the movement of particles to the membrane surface could result from the convection caused by the permeate flow and from inertial

Table 2
Filtration with 2.7 and 0.65 mm axial fibres with and without bubbling[a]

Fibres D_0 (mm)	U_{SG} (m/s)	U_{SL} (m/s)	Initial flux (LMH)	Final flux (LMH)	D_J (%)
2.7	0	0.2	59.6	20.6	65
	0	0.4	61.8	22.9	62
	0.2	0.2	65.4	31.3	52
0.65	0	0.2	64.4	21.9	66
	0	0.4	58	27.1	53
	0.2	0.2	70.8	50.3	29
	0.2	0.2	58	42.5	27

[a] U_{SG}, U_{SL}: the superficial gas and liquid velocity.

impaction. The latter is caused by the inertial deviation of particles from the sudden curving flow streamlines around the transverse fibres. The inertial impaction may take place in the front of the fibre, as well as in the back of the fibre due to the action of the wake vortices [12–14].

Particle deposition on the membrane surface depends on the balance between the particle movement to the membrane surface and the back transport from the membrane. For filtration with transverse flow, particle back transport can be caused by shear stress around the fibre, which results in a lift force on the particles in the area near the wall [12], and by fibre movement.

The main difference between the small fibre and the larger fibre for filtration with transverse flow is the shear stress and fibre movement. According to Schlichting [7], the shear around a cylinder in transverse flow at a given point before the boundary layer separation point is proportional to the free stream velocity to the 1.5 power and inversely proportional to the radius of the cylinder to the 0.5 power. This means that there is a higher wall shear in the front part of the smaller fibres. The difference in fibre movement at the same crossflow conditions between 0.65 and 2.7 mm fibres was assessed qualitatively by the microscopy observation. This indicated that the fibre movement caused by the transverse flow is more significant for the 0.65 mm fibres than for the 2.7 mm fibres. Thus, the higher wall shear and enhanced fibre movement could explain the lower flux decline in filtration with the smaller fibres.

For filtration with transverse flow, the performance with 2.7 mm fibres was insensitive to increase in crossflow velocity over the range tested. This can be explained from the effect of inertial impaction on filtration. Although the small fibre may have a high impacting efficiency [13], the effect of inertial impaction on filtration with the smaller fibres seems to be controlled by the higher shear around the smaller fibres and the enhanced fibre movement. For the 2.7 mm fibres, the relatively large fibre diameter leads to an increase in the likelihood of capture of particles upon each impact [15]. Meanwhile, the lower shear and reduced fibre movement with the larger fibre make it possible that inertial deposition exerts a significant influence on particle deposition.

The influence of inertial impaction on filtration with the 2.7 mm transverse fibres was confirmed by microscope/video observation of the characteristics of deposition. Observations were carried out with a fibre bundle of 8 mm × 2.7 mm fibres arranged in the cell in the transverse position with a spacing of 5 mm. After 4 h filtration of 0.1 g/l yeast suspension, the microscope and video-camera were used to observe particle deposition on the fibres. These observations indicated that there was a significant deposition on the front and back of the first fibre (Fig. 11(a)). This pattern of deposition indicates that inertial deposition played an important role in filtration of yeast with 2.7 mm fibres. However, an interesting phenomenon revealed by the observation is that the depositions on the front face of all the other downstream fibres were dramatically reduced (Fig. 11(b)). In order to understand the mechanisms that led to the decrease in deposition on the front face of the downstream fibres, we studied the flow around the fibres. It was observed that the decreased deposition on the front face of all down stream fibres resulted from the effect of inter-fibre vortices on particle deposition. The inter-fibre

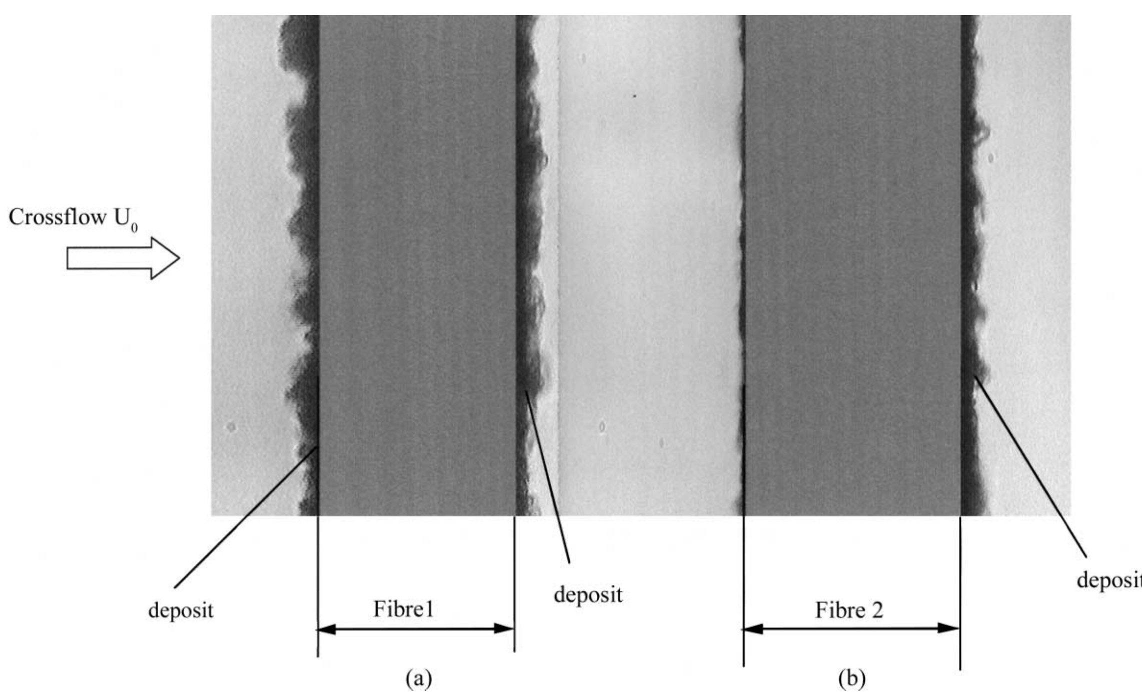

Fig. 11. Images of fibres after 4 h filtration of 0.1 g/l yeast suspension with a 2.7 mm transverse fibre bundle without bubbling (eight fibres, spacing = 5 mm): (a) the first fibre, (b) the second fibre.

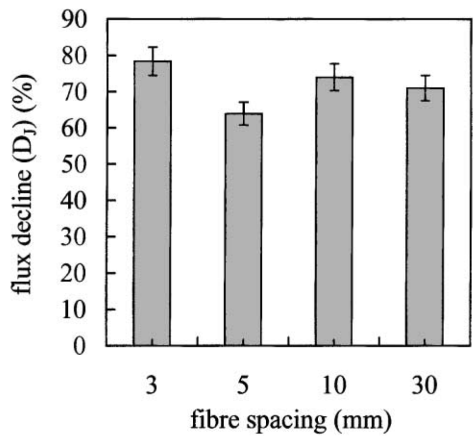

Fig. 12. Effect of fibre spacing on flux decline in filtration of 5 g/l yeast suspension with 2.7 mm fibres without bubbling (error $< \pm 2.5$ with repeated experiments).

vortices tended to bring the particles to the back of the upstream fibres, and sweep particles from the front face of the downstream fibre if the fibre spacing was close to the diameter of the vortices. The effect of the inter-fibre vortices on particle deposition on the front face of the down stream fibres implies that for the relative large fibres the filtration performance can be improved by arranging the fibres in an optimal spacing. Fig. 12 shows the effect of fibre spacing on flux decline for 120 min filtration of 5 g/l yeast suspension with the 2.7 mm transverse fibres. The results show a lower flux decline with the 5 mm spacing which was observed to be the approximate magnitude of the diameter of vortices behind the fibres.

4.2. Filtration with bubbling

The hydrodynamic environmental for filtration with bubbling is significantly different from that in filtration with single-phase flow. With air injection, a two-phase flow forms between fibres and this unstable flow results in a significant enhancement in fibre movement.

Comparing the results obtained with and without bubbling, it can be noted that for the 0.65 mm fibres the effect of fibre orientation considerably decreased. The decreased effect of fibre orientation implies that the process tended to be controlled by the turbulence caused by the two-phase flow [10].

In addition, with the model crossflow cell, the observed features of the two-phase flow with axial and transverse orientation were different. With axial fibres, bubbles rise along the fibres and a slug flow forms between fibres, while with transverse fibres, bubbles can be trapped between fibres and moved from left to right at some frequency [10]. The higher flux obtained with axial orientation for filtration with bubbling indicated that the rising bubbles are more effective in control of particle deposition.

5. Conclusions

This paper describes the effect of fibre orientation on filtration of biomass without and with bubbling. The experimental results for filtration of yeast with different fibre diameters indicate that the effect of fibre orientation on the filtration process could be considerably different with different filtration conditions (crossflow velocity, with or without bubbling) and fibre diameters. For filtration without bubbling, a significant benefit can be obtained from transverse flow with the small fibre, but for the relatively larger fibre (2.7 mm fibre) the benefit of the transverse flow becomes insignificant due to the effect of inertial deposition. Comparison between the smaller and the larger fibres indicated that the small fibre is much better than the larger fibre for filtration with transverse flow. On the other hand, for filtration with bubbling, the results showed that axial was better than transverse for both fibres. However, with bubbling, the overall effect of fibre orientation on filtration decreased because the process tended to be controlled by the turbulence caused by the two-phase flow. Nevertheless, this study suggests that for submerged hollow fibres in bubble-enhanced systems, such as the membrane bioreactor, the preferred fibre orientation should be axial (vertical) rather than transverse (horizontal).

Acknowledgements

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