Performance of individual fibers in a submerged hollow fiber bundle

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Abstract Hollow fiber membranes are popular as they have a high specific membrane area. To take advantage of this, it is necessary to pack the fibers into closely packed bundles. The fibers in different positions in the bundle behave differently as they are exposed to different hydrodynamic conditions. In this paper, a ‘model’ bundle of 9 fibers was tested in a setup which provides flow measurement from individual fibers and the same suction pressure in each fiber. The parameters studied were packing density, cross flow velocity, feed concentration and bubbling. It was found that a low cross flow velocities, high pressures and high feed concentrations, the surrounded (center) fiber performed very poorly compared to the fibers at the corner and the sides. Under these conditions, the overall performance of the bundle was much worse that of a single fiber.

Keywords Fiber bundles; fiber performance; fouling; hollow fibres; submerged

Introduction

The use of submerged hollow fibers for low pressure microfiltration and ultrafiltration has gained popularity due to the elimination of the pressure vessel and the high specific membrane area possible. This concept has allowed the development of systems with small footprint for water treatment plant and a variety of wastewater treatment processes, such as the treatment of high strength industrial wastewater and membrane bioreactors (Noor et al., 2002; Chiemchaisri et al., 1993).

The productivity of hollow fiber membranes is related to both flux as well as membrane packing density. A higher membrane packing density would increase productivity, as long as flux is not detrimentally affected. In early work on submerged hollow fibers, Kiat et al. (1992) studied the effect of packing density on flux decline and clogging mechanisms within the fiber bundle. For a kaolin clay suspension, increasing the packing density decreased steady state flux to a minimum which then increased slightly. Interestingly, the flux did not decrease even when the packing density increased to the maximum possible. This suggests that the cake layer resistance formed on the bundle surface was negligible, and no clogging of the fiber surfaces was observed. From their observations, the packing density should be as high as possible to get maximum efficiency from a membrane plant. However, this conclusion would be limited to certain types of feed and tolerance of very low fluxes.

The optimization of packing density should depend on the attainable permeate flux. For example, the net flow rate varies with external diameter of the fiber and the void fraction and an optimum condition is observed (Serra et al., 1998). The filtering area increases when the void fraction of the bundle or the fiber diameter are reduced, however, a reduction in these two parameters increase the pressure drop inside the fibers and in the bundle. A higher net flow rate tends to shift the optimum combination towards larger diameters and more void space. The optimum packing density would also depend on whether aeration is applied. High fiber density can result in both smaller bubbles, and hence less turbulence in their wakes, as well as a less favourable inter-fiber interactions.
hydrodynamic environment (Chang and Fane, 2001). Narrower channels result in smaller and slower bubbles around the fibers.

This study is based on the assumption that each fiber within a bundle could develop different degrees of fouling, as each fiber in the bundle experiences different hydrodynamic conditions. The fibers in the center of the bundle would experience lower cross flow velocity, while the fibers nearer the edge of the bundle would experience higher cross flow velocity. As submerged hollow fibers become a more popular design concept, it becomes necessary to ensure that the productivity of the bundle is at its optimum level.

The objective of this study is to determine the performance of individual fibers in a bundle as a function of operating conditions. The parameters studied include feed concentration, packing density, cross flow velocity and the effects of bubbling.

**Experimental setup**

Experiments were based on a ‘model’ bundle of fibers with a ‘model’ feed. The hollow fiber module had a flow channel that was 1 m long, with a 20 mm by 20 mm cross section. The feed solution was bentonite, which had an average particle diameter of 5 microns. The fibers were made of polyacrylonitrile (PAN), with an inner diameter of 0.6 mm and an outer diameter of 0.8 mm. The nominal pore size of the membrane was 0.5 microns and the clean water permeability of the fibers was about 1.7 l/m²/hr/kPa, and varied about +/− 8%.

To obtain varying packing densities, metal plates perforated with holes at different spacing were made. The fibers were inserted into 2 plates located at both ends of the module and pulled taut. The fibers were sealed at one end, and individually connected to a length of tubing at the other. These tubings were connected to ports in a vacuum chamber, where plastic cylinders collected the flux from each fiber separately. The vacuum chamber was connected to a pump that could maintain a negative pressure of up to 60 kPa. With the vacuum chamber arrangement, each fiber in the bundle experienced the same driving pressure.

To determine how the flux changed with time, a 2 mm hole extended from each port and the number of drops per minute discharged was counted. By dividing the total number of drops by the total volume in the cylinder, the volume per drop could be calculated. It was found that the average size of each drop was about 0.03 to 0.04 liters. A video camera was used to record the number of drops that fell from the port per minute. With this information, the rate of change of the flux could be determined. In all the experiments, the pressure was stepped from −10 kPa to −50 kPa in 10 kPa decrements. The pressure was maintained for 1 hour, after which the process was stopped, and the cylinders taken out and weighed. After weighing, the cylinders were replaced and the pressure was decreased by 10 kPa, and run for another hour, and so on.

A total of five series of experiments were carried out, and the conditions are shown in Table 1. A packing density of 44% corresponds to a 0.5 mm distance between fiber

<table>
<thead>
<tr>
<th>Series name</th>
<th>Packing density</th>
<th>No. of fibers</th>
<th>Feed concentration</th>
<th>No. of tests</th>
<th>Considers the effects of</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFBX</td>
<td>44%</td>
<td>9</td>
<td>1.0 g/1</td>
<td>6</td>
<td>Cross flow</td>
</tr>
<tr>
<td>HFBY</td>
<td>28%</td>
<td>9</td>
<td>1.0 g/1</td>
<td>6</td>
<td>Packing density</td>
</tr>
<tr>
<td>HFBH</td>
<td>44%</td>
<td>9</td>
<td>2.0 g/1</td>
<td>4</td>
<td>Feed concentration</td>
</tr>
<tr>
<td>HFBL</td>
<td>44%</td>
<td>9</td>
<td>0.5 g/1</td>
<td>4</td>
<td>Feed concentration</td>
</tr>
<tr>
<td>HFBBubble</td>
<td>44%</td>
<td>9</td>
<td>2.0 g/1</td>
<td>1</td>
<td>Bubbling</td>
</tr>
<tr>
<td>HFSingle</td>
<td>Single</td>
<td>1</td>
<td>1.0 g/1</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
surfaces, while a 28% packing density corresponds to a 1 mm distance between fiber surfaces. In each series, the recirculation velocity was varied.

Experimental results and discussion
The results are discussed below under four board categories: the performance of the bundle as a whole, the deviations between fibers with the same position in the bundle, the performance of each individual position in the bundle and the effects of bubbling.

Performance of the bundle
To determine the performance of the bundle as a whole, the average flux from the fibers in the bundle was compared to the performance of a single fiber (series HFSingle in Table 1) under the same conditions. At low pressures (and low fluxes), there was no significant difference between the performance of the bundle as compared to the performance of a single fiber. However, as pressure (and flux) increased, the differences become more obvious, especially at low cross flow velocities. Higher packing densities and higher feed concentrations cause the greatest drop in performance at high pressures.

At 50 kPa (Figure 1), and 0.02 m/s crossflow velocity, the flux obtained when packing the bundle at 44% (HFBX) dropped by 25% as compared to a single fiber. At a packing density of 28% (HFBY), the flux obtained dropped by about 10%. At a high feed concentration (HFBH), the flux obtained dropped by almost 75%. As cross flow velocity increases, the fibers in the bundle start to behave more like single fibers.

The difference between the fibers packed into a bundle and a single isolated fiber can be related to two factors. The first factor is the hydrodynamic effect and the second is geometric effect (the interference of the cake layers) in the bundle. At higher packing densities, there will be more stagnant areas within the bundle. These stagnant areas cause the shear stress experienced by the fibers in the bundle to be less than that of a single fiber. This causes a build up of cake, and rapid fouling to occur. This problem is exacerbated by low cross flow velocity, which hinders fluid from penetrating into the fiber bundle and the effect is accelerated as local blocking or obstruction occur. The cake layers would also build up rapidly under low crossflow velocities. As these cake layers get thicker, they would start to touch each other, then start to merge, and clogging (interstitial blockage) would occur. This is detrimental to the performance of the bundle. Increasing the concentration of the feed causes the fibers to foul much more rapidly, which would explain the poor performance of the HFBH series of experiments in Figure 1.

Standard deviations
The fibers were positioned on a $3 \times 3$ matrix and numbered from one corner, so that fibers 1, 3, 7 and 9 occupied corners, 2, 4, 6 and 8 were sides and 5 was central.
Although fibers 1, 3, 7 and 9 (corner) as well as fibers 2, 4, 6 and 8 (side) were in the same position in the bundle, the flux from these fibers were, in some cases, dramatically different from each other. For example, at a cross flow velocity of 0.005 m/s and a packing density of 44%, the flux from fibers 2, 4, 6 and 8 were 37.1, 46.9, 21.2, and 21.9 l/m²/hr respectively. In order to quantify the variation of the flux, the standard deviation was used. The flux from each of the fibers was normalized with the average flux, and then standard deviation calculated. In the above example, the average flux was 31.76 l/m²/hr, and the normalized values are 1.17, 1.48, 0.66 and 0.69 for fibers 2, 4, 6 and 8 respectively. The standard deviation of these values is 0.39.

In general, Figure 2 shows that the standard deviations either increased with pressure, or were relatively constant. The standard deviations also varied with packing density, cross flow velocity and feed concentration. As shown in Figure 2, at a packing density of 44% at low crossflows (0.005 m/s to 0.04 m/s) the standard deviation was 0.4 to almost 0.6. As cross flow velocity increased (0.08 to 0.32 m/s) the standard deviation decreased to around 0.1, indicating a more uniform distribution of flux among the fibers in the same positions.

At a lower packing density of 28%, the standard deviation did not vary much at any cross flow velocity or pressure and was less than 0.2. The same trend was also seen at very high feed concentrations. Thus at a feed concentration of 2 g/l, the standard deviation was also stable at about 0.2, and no pattern could be discerned from the graph. In contrast as described above, at low feed concentrations (Figure 2), the standard deviations of the fibers are higher at low cross flow velocities and lower at high cross flow velocities.

Although the fibers were in the same position, there were differences in the fluxes of up to 40% in some cases. Such large deviations occurred reproducibly but not necessarily in the same locations. The reason for these differences is believed to be the way cake builds up on the fiber. Observations after the experiments were conducted show that some fibers were stuck together, and were surrounded by a dense layer of cake, while other fibers are not.

The build up of cake is not likely to be uniform throughout the fiber surface. This is due to the complexity of flow as it enters the bundle. Hence, it is possible that some of the fibers would get stuck together as their cake layers merge, and then these fibers would foul rapidly, while the other fibers would not foul as rapidly. This merging of cake layers has been observed when filtering activated sludge (Kiat et al., 1992). When feed concentration is high, the standard deviation is lower than when the feed concentration is low. This could be due to the fact that cake layers build up rapidly when the feed concentration is high. As the cake layers grew, they encompassed the entire fiber bundle, resulting in equally poor performance for all the fibers. In contrast, at lower feed concentrations, the cake layers were thinner, and therefore the fibers did not foul as rapidly. This resulted in a more uniform distribution of flux among the fibers in the same positions.

**Figure 2** Standard deviation for series HFBX (packing density 44%, 1 g/L)
concentrations, the cake layers do not grow as rapidly and this leads to the possibility of preferential growth of the cake in certain directions, which would cause the performance of certain fibers to degrade and not others. It is should be noted that local blockage is a self-accelerating phenomenon as an incipient blockage will reduce local flows which would encourage further deposition.

Comparisons within the bundle

In the 3 by 3 matrix of fibers, there were only 3 unique positions, the centre fiber (Fiber 5), the corner fibers (Fibers 1, 3, 5 and 9) and the side fibers (Fibers 2, 4, 6 and 8). Besides the flux obtained from the fibers after an hour, the rate at which the flux changed on a minute by minute basis was also determined for fiber 5, representing the centre fiber, fiber 6, representing the side fiber, and fiber 7, representing the corner fiber. A typical flux-time graph is shown in Figure 3.

To aid in the analysis, a parameter was defined to characterise the performance of a given fiber relative to all fibers:

\[
\alpha = \frac{\text{Flux from specified fiber}}{\text{Average flux of all fibers in bundle}}
\]

In all the experiments conducted, the alpha values for fibers 6 and 7 were close to unity, i.e. they performed close to the average of the fibers in the bundle. The alpha values of the corner fiber (about 1.1) were slightly higher than that of the side fibers (about 1.0).

For the centre fiber, increasing the transmembrane pressure (increasing flux) decreased the alpha value and more so when the cross flow velocity was low. This is shown in Figure 4.

At 50 kPa (Figure 5), and a cross flow velocity of 0.02 m/s, increasing packing density to 44% (HFBX) caused alpha to fall to 0.6. this means that the middle fiber was only contributing 60% of the average flux of the fibers. At a high feed concentration (HFBH), there was no contribution of the flux at all, in effect the fiber had been completely fouled and contributed nothing to the performance of the bundle. For a packing density of 28% (HFBY), the alpha value was about 0.9, and at low feed concentrations for higher packing density (HFBL), the alpha value was 0.78. In all cases, the alpha values approached unity as cross flow velocity increased.

The side and corner fibers would have experienced the main flow over much of their surface, and would have had a higher shear rate over those surfaces. This should have caused the performance of these fibers to be better than that of the centre fiber, and this was true for all the cases studied. The corner fibers had slightly more surface exposed to

![Figure 3](https://iwaponline.com/wst/article-pdf/51/6-7/165/435268/165.pdf)  
**Figure 3** Flux-time relationship for series HFBX, crossflow velocity of 0.005 m/s
the main flow as opposed to the side fiber, and this explains why the corner fibers performed somewhat better than the side fibers.

For the centre fiber, the performance would degrade significantly once cake accumulates in such a way that it blocks flow towards the fiber. This is the self-accelerating phenomenon referred to earlier. As pressure increases, the cake layer grows, and blocking occurs more quickly. This was also true for low cross flow velocities. This would cause the performance of the centre fiber to degrade more quickly than the corner or side fibers.

By spacing the fibers further apart, it is possible to slow this process, or even avoid it altogether, as shown in series HFBY (Figure 5). It can be seen that the performance of the centre fiber was close to that of the other fibers in this case. At high feed concentrations (HFBH), coupled with low cross flow velocities, the centre fiber was completely blocked and no flux was measured. These observations are different from the early work of Kiat et al. (1992), probably due to the larger average fluxes observed in the current study.

Bubbling

When bubbling was applied, there was a marked improvement in the performance of the bundle. Comparing the average of flux from the fibers, at 50 kPa, there was a more than tenfold increase in the flux (Figure 6). Furthermore, the standard deviations between the fibers in the same position fell to less than 0.1. The alpha values for all the fibers were between 0.95 and 1, eliminating the differences between them.

Whilst the overall benefits of bubbling are well established (Cui et al., 2003), these results show dramatically the effect at the individual fiber level in the bundle. Several mechanisms for the enhancement of the performance of membranes due to gas sparging have been identified (Cui et al., 2003), including bubble induced secondary flow, physical displacement of the mass transfer boundary layer, movement of the fibres and pressure
pulsing caused by slugs. The challenge for the designers of submerged hollow fibre systems is to maximize the interaction of the bubbles with the population of fibres within the bundle. We aim to address this challenge in our future work.

Conclusions
The results of this study show that:

1. The combined effects of low cross flow velocity and high pressure (initially high flux) cause the fiber bundle performance to be much worse than that of a single fiber. These effects also cause large variations in the performance of fibers in the same position in the bundle. This is due to difference in the way the cake layer builds up. Moreover, under these conditions, the surrounded (center) fiber performs much worse than the outer fibers.

2. Lowering the packing density to 28% leads to a marked improvement in the bundle performance as measured against the single fiber. Also, the negative effects of low cross flow velocity and high pressure are not as acute as when packing density is high. This is because the fibers are further apart, and the cake layers from adjacent fibers cannot interfere with each other.

3. Increasing the feed concentration has a very negative effect on fiber performance. At a low cross flow velocity and high pressure, the surrounded (center) fiber becomes completely blocked and produces no flux. This is caused by the cake layer growing rapidly to block up the void space around the fiber. The rapid growth of the cake layer contributes to the fact that the fibers in the same position have near uniform performance.

4. At low feed concentration, the performance of the bundle is better. However, the cake layer builds up slowly, and this gives the opportunity for some of the fibers to bond together, and this self-accelerating phenomena leads to significant differences between individual fibers.

5. Bubbling vastly improves the performance of the fiber bundle. This is probably due to the bubbles disturbing the cake layers so that they do not become thick enough to interfere with each other. A challenge for system designers is to achieve this bubble effect throughout the population of fibers in a large bundle.

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