Improving the performance of dead-end ultrafiltration systems: comparing air and water flushing

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Abstract A cleaning protocol that effectively removes fouling from hollow fiber UF systems without excessive use of chemicals, product water or (long) down time is needed. Cross flushing with UF feed water has been reported to increase the net flux of hollow fiber systems by reducing the frequency of backwashing, the consumption of permeate and the system down time. In this study, the flux restoration achieved in a vertical and horizontal UF system employing an intermittent water and water/air cross flush were compared. The flux restoration in the vertical UF system was not improved by the addition of air to the water flush and a maximum flux restoration of 82% was achieved, irrespective of the presence of air. Similarly, in a horizontal ultrafiltration system, a maximum flux restoration of 82% was also achieved with a water flush (v = 1.63 m/s). However, the addition of air to the water flush decreased the flux restoration to 40% at the highest water/air ratio (33% air). Low flux restoration in the horizontal system was attributed to residual air in the module after cross flushing. Flushing with water alone (v = 1.63 m/s) yielded a wall shear stress of 16 Pa compared with 130 Pa and 279 Pa in the liquid film surrounding the air slugs in the horizontal and vertical UF system, respectively, with a water/air ratio of 2:1. Despite the high shear force on the cake layer accumulated when air was added to the system, the maximum flux restoration was 82% both with and without air. This was attributed to the fact that it was the filtration mechanism and not the shear force on the cake layer that limited flux restoration during cross flushing. To improve the flux restoration that can be achieved by the cross flushing process, the filtration mechanism must be manipulated to minimize blocking filtration and induce cake filtration from the beginning of each filtration cycle.

Keywords Ultrafiltration; dead-end; flux restoration; water flush; water/air flush; residual air; wall shear stress; liquid film; filtration mechanism; blocking filtration; cake filtration

Introduction

Dead-end ultrafiltration systems depend on frequent backwashing and chemical cleaning to remove fouling and restore the system flux and/or pressure to its original level. The water losses and down time associated with backwashing and chemical cleaning can only be decreased if the frequency of these cleaning methods can be reduced. To achieve this goal an alternative cleaning protocol that does not require chemicals, product water or (long) down time, but still effectively removes fouling is needed.

Intermittent cross flushing with UF feed water has been reported to increase the efficiency (net flux) of dead-end hollow fiber systems by reducing the frequency of backwashing, the consumption of permeate and the down time of the system (Kennedy et al., 1998). The use of two-phase, gas-liquid flow to promote turbulent conditions within hollow fiber systems has also been reported to substantially improve product fluxes in many cross-flow applications (Cabassud et al., 1997; Mercier et al., 1997). The hydrodynamic disturbances resulted in an increase in both the wall shear stress and the superficial liquid velocity which led to a significant enhancement of the permeate flux (Cabassud et al., 1997). The intermittent injection of air into the feed stream (air-flush) was also reported to enhance the flux and reduce the consumption of chemicals in filter backwash water applications (van der Meer et al., 1999).
Despite the many advantages of cross flushing, particles, colloids and/or macromolecules deposited within the pores of the membrane (complete blocking) or adsorbed on the pore wall (standard blocking) or on the membrane surface cannot be removed by this process. In theory, cross flushing can only remove foulants that have accumulated on the membrane surface (cake filtration). Therefore, the efficiency of the cross flushing process is controlled by the filtration mechanism and in particular by the occurrence of cake filtration, which is in turn controlled by the relationship between the particle size distribution of the UF feed water and the pore size distribution of the UF membrane.

Since a range of particle sizes exist in most natural water systems, a certain amount of blocking filtration (complete/standard blocking) will always occur prior to cake filtration. To maximize the efficiency of cross flushing, cake filtration must occur from the beginning of each filtration cycle, thus preventing particles, colloids and macromolecules from entering the pores and adsorbing on the membrane wall. Thus, the frequency of backwashing and chemical cleaning can be reduced and the efficiency of UF systems increased if cake filtration can be induced from the start of each filtration cycle. Recent advances in the manipulation of the filtration mechanism involve the use of in-line coagulation and precoat technology (van der Meer et al., 1999, Galjaard et al., 2001).

**Background**

In dead-end ultrafiltration systems, the thickness of the cake layer increases with the filtration time leading to flux decline. The use of a two-phase gas-liquid flow to promote turbulent conditions in membrane filtration is expected to rapidly remove the developed cake. The hydrodynamic disturbances result in an increase in both wall shear stress and superficial liquid velocities which may lead to a significant enhancement of the permeate flux (Mercier et al., 1997).

Gas-liquid two-phase flow, in both the horizontal and vertical position, can be divided into certain patterns such as, bubble flow, slug flow, cap flow and annular flow. Which flow pattern exists within a tube depends on many factors i.e. flow rates, fluid properties, conduit shape or inclination, velocity, shape of the interface etc., and makes the prediction of flow patterns very difficult. In order to simplify matters, the results of photographic observations at low, medium and high water flow rates and over a range of gas flow rates were adopted from (Govier and Aziz, 1972), for both vertical and horizontal systems. The difficulty with existing scale drawings and the associated flow patterns is that they were experimentally derived using a 2.6 cm pipe, while the diameter of the hollow fiber used in this study was 1.5 mm.

The wall shear stress \(\tau_w\) in the vertical direction is:

\[
\tau_w = \frac{1}{2} f \rho_L j^2
\]

With \(f\) the friction factor, \(\rho_L\) the liquid density (kg/m\(^3\)) and \(j\) the average mixture velocity (m/s).

The shear stress \(\tau_w\) in the liquid film surrounding an air slug in the vertical direction is:

\[
\tau_w = \frac{1}{2} C_D \rho_L V_r^2
\]

With \(C_D\) the overall drag coefficient and \(V_r\) the relative velocity between the bubble \((V_b)\) and the fluid \((V_f)\) in vertical two-phase flow (m/s).

A model proposed by Hubbard and Dukler (Govier and Aziz, 1972) was used to estimate the wall film shear stress in a horizontal system. An average slug unit was assumed to consist of an average liquid slug plus associated gas bubbles and a liquid film. The friction
component due to the liquid slug may be expressed by using a form of the Fanning equation where the friction factor \( f \) depends on the Reynolds number of the mixture.

The shear stress in the liquid slug \( \tau_w \) in the horizontal direction is:

\[
\tau_w = \frac{1}{2} \cdot f \cdot \rho_L \cdot V_L^2
\]

(3)

where, \( V_L \) is the average actual liquid velocity (m/s).

To determine the shear stress in the liquid film around the slug, the concept of flow over immersed bodies was assumed. As an immersed body moves through a fluid, an interaction between the body and the fluid occurs. The resultant force in the direction of the upstream velocity is termed as the drag, \( D \) (Young et al., 1997). This net force consists of friction drag that is due directly to the shear stress, \( \tau_w \), on the object and pressure drag, which is due to the pressure on an object. The length of an air slug was assumed to be about 16\( D \) (16 times the bubble diameter) (Dukler and Taitel, 1986) and the bubble/slug was assumed to be non-deformable when moving along the fiber and it was assumed that it occupied almost the whole cross sectional area (internal diameter of 1.5 mm) of a fiber. A schematic of slug flow is presented in Figure 1.

The wall shear stress \( \tau_w \) acting on the surface of an air slug is:

\[
\tau_w = \frac{1}{2} \cdot C_D \cdot \rho_L \cdot V_f^2
\]

(4)

It was assumed that the shear stress on the surface of an air slug is equivalent to the shear stress exerted on the fiber wall.

**Experimental**

Dead-end filtration was carried out with surface water and/or wastewater at a constant trans-membrane pressure (TMP) of 0.2 bar. The flux was recorded automatically by computer using a software package “Hypfilt”, supplied by Kiwa N.V. When the initial flux declined by 20% (filtration cycle had a duration of ca. 15–20 mins.), a cross flush was carried out by applying a water or water/air along the fiber (from the feed side to retentate side), with the permeate valve closed. A pump \( (P_{bw}) \) was used to supply water with high velocity across the module, creating turbulence and shear force inside the fibers. After each flush (water or water/air), the flux restoration was estimated by measuring the clean water flux \( \text{CWF} \) of the system and comparing it to the original \( \text{CWF} \) of the system (measured using de-mineralized water and a clean membrane). To initiate a water flush, valves \( V_4, V_6, V_7 \), and \( V_3 \) were opened. The cross flush velocity was adjusted using valve \( V_{10} \). When flushing with water/air, the air supply line was connected to the system by opening valves \( V_8 \) and \( V_9 \) in addition to the valves used for flushing with water alone (Figure 2).

Characteristics of the surface water and wastewater used in the UF tests are presented in Table 1.
The characteristics of the UF hollow fiber membrane module (X-FLOW) used in this study are given in Table 2.

### Results and discussion

#### Effect of flushing with water on the flux restoration in a horizontal UF system

A horizontal UF module was fed with surface water at a constant TMP of 0.2 bar. The turbidity of the surface water was 10-15 FTU in all tests. When the flux of the UF system decreased by 20% of the initial value, a flush with water was employed to restore the flux. The effect of cross flushing time and velocity on the flux restoration in a horizontal UF module is presented in Figure 3.

Flux restoration increased from ca. 65% at a cross flush velocity of 0.88 m/s to ca. 82% at a velocity of 1.63 m/s. This was attributed to a change from laminar flow (Re: 1315) at a velocity of 0.88 m/s to turbulent flow (Re: 2445), when the velocity was increased to 1.63 m/s. A further increase in the cross flush velocity to 1.98 m/s (Re: 2970) did not significantly improve flux restoration above 82%. Similarly, increasing the cross flush time from 10 to 30s did not significantly improve the flux restoration above 82%.

#### Effect of cross flushing with air/water on the flux restoration in a horizontal UF system

The total flow rate of (gas + liquid) for each water/air ratio was varied from 0.88 m/s (gas = 0.88 m/s, liquid = 0 m/s) to 1.98 m/s (gas = 0.88 m/s, liquid = 1.1 m/s) and the effect of these conditions on flux restoration was analyzed. The results indicated that the flux restoration was not significantly affected by the air/water ratio.

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**Table 1** Characteristic surface water and wastewater

<table>
<thead>
<tr>
<th>Experimental conditions</th>
<th>Turbidity (FTU)</th>
<th>Characteristic of feed water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface (canal) water</td>
<td>10-15</td>
<td>TSS (mg/l) 10-30, COD (mg/l) 10-20, TOC (mg/l) 10-20, pH 7.9-8.2</td>
</tr>
<tr>
<td>Wastewater</td>
<td>&lt; 5</td>
<td>TSS (mg/l) 10-20, COD (mg/l) 100-200, TOC (mg/l) &lt;10, pH 7.5-8.2</td>
</tr>
</tbody>
</table>

**Table 2** Characteristics of membrane modules in the research

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Membrane Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>PES/Polysulphone M5</td>
</tr>
<tr>
<td>MWCO (Dalton)</td>
<td>150,000</td>
</tr>
<tr>
<td>Length (m)</td>
<td>1.0 m.</td>
</tr>
<tr>
<td>Module diameter (cm)</td>
<td>3</td>
</tr>
<tr>
<td>Internal Fiber diameter (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Membrane surface area (m²)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The characteristics of the UF hollow fiber membrane module (X-FLOW) used in this study are given in Table 2.
l/hr) to 1.63 m/s (520 l/hr) and 1.98 m/s (630 l/hr). The mean cross flush velocity was defined as \( j = j_G + j_L \). The water/air ratio was varied from 2:1 to 20:1 and the cross flush time was varied from 10 to 30 seconds. For the aforementioned range of water/air ratios and cross flush velocities, the expected flow pattern was between slug flow and elongated bubble flow (Grovier and Aziz, 1972). However, slug flow was assumed in all cases in horizontal modules due to the difficulty of finding equations to describe elongated bubble flow in horizontal systems.

The results of cross flushing with water/air in a horizontal UF module are presented in Figure 4. Decreasing the amount of air in the cross flush appeared to increase the flux restoration from 40% at a low water/air ratio of 2:1 (33% air) to 82% at a water/air ratio of 10:1 (10% air). Further increasing the water/air ratio to 20:1 (5% air) did not significantly improve the flux restoration above 82%. It must also be pointed out that when the air was shut off completely and the cross flush was performed with water alone \( (v = 1.63 \text{ m/s}) \), a flux restoration of 82% was also achieved. Increasing the cross flushing time from 10 to 30 s and/or increasing the cross flushing velocity from 1.63 to 1.98 m/s did not significantly improve the flux restoration above 82%.

The low flux restoration achieved in the horizontal UF module when large amounts of air were employed in the cross flush (low water/air ratios) was attributed to residual air in the module after cross flushing. Visual inspection revealed the presence of air bubbles in the cross flush water after the air supply was shut off (Table 3). At least 5 minutes were necessary to remove the air bubbles from a horizontal UF module when it was cross flushed for 10 s with a water/air ratio of 2/1. The time was reduced to 10 seconds when the water/air ratio was increased to 20/1. The exact mechanism by which flux restoration was hindered by residual air in the module is not clear, but it is expected that residual air can cover the membrane pores and decrease the filtration area in subsequent filtration cycles. Residual air may be removed by backwashing or by a subsequent water flush directly after the water/air flush. However, the cross flushing process will become more complicated and the system down time will increase.

Comparing cross flushing with water and water/air in vertical and horizontal systems

A comparison of the flux restoration achieved by cross flushing with water/air and with water alone in a horizontal and vertical UF module is presented in Figure 5. A mean cross

Figure 3 Effect of cross flushing (CF) time and velocity on flux restoration in a horizontal UF module

- CF at 0.88 m/s
- CF at 1.63 m/s
- CF at 1.98 m/s

Flux Restoration (%)

Cross Flushing Time (s)

10 s 20 s 30 s
flush velocity of 1.63 m/s (Re : 2445), a cross flush time of 10 seconds and water/air ratios from 2/1 to 20/1 were used for the comparison. Slug flow was assumed to occur at a water/air ratio of 2:1 and for all other water/air ratios (4:1 to 20:1) bubble flow was assumed to occur, in the vertical UF module. The occurrence of slug flow was also reported in a vertical hollow fiber UF system (Cabassud et al., 1997).

Figure 4  Effect of the water/air ratio on the flux restoration in a horizontal UF module (cross flush velocity: 1.63 m/s, cross flush time: 10s)

Table 3  Residual air bubble effect in horizontal UF modules

<table>
<thead>
<tr>
<th>water/air ratio</th>
<th>*Time required to remove air from a horizontal UF module (1m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/1</td>
<td>&gt; 5 min</td>
</tr>
<tr>
<td>4/1</td>
<td>≈ 1 min</td>
</tr>
<tr>
<td>8/1</td>
<td>≈ 48 sec</td>
</tr>
<tr>
<td>10/1</td>
<td>≈ 50 sec</td>
</tr>
<tr>
<td>20/1</td>
<td>≈ 10 sec</td>
</tr>
</tbody>
</table>

* Required time to remove most of the air bubbles from the module after turning off the air supply valve

Figure 5  Comparing water and water/air cross flushing in a vertical and horizontal UF system

flush velocity of 1.63 m/s (Re : 2445), a cross flush time of 10 seconds and water/air ratios from 2/1 to 20/1 were used for the comparison. Slug flow was assumed to occur at a water/air ratio of 2:1 and for all other water/air ratios (4:1 to 20:1) bubble flow was assumed to occur, in the vertical UF module. The occurrence of slug flow was also reported in a vertical hollow fiber UF system (Cabassud et al., 1997).
From Figure 5, it can be observed that in the vertical UF module, 82% flux restoration was achieved at a mean cross flush velocity of 1.63 m/s and with a water/air ratio of 2:1 (33% air). Flux restoration in the vertical system did not show any significant decrease when the amount of air in the water/air cross flush was reduced from 33% to 5%. Moreover, in the vertical UF module a flux restoration of 82% was also achieved when the air was shut off completely and the water velocity maintained at 1.63 m/s. Increasing the mean cross flush velocity to 1.98 m/s, the cross flushing time to 30 s and reducing the water/air ratio to 1:1 (50% air) did not significantly improve the flux restoration above 82% in the vertical UF system. The main advantage of using water/air is the saving in raw water. Employing a water/air cross flush in a vertical UF system can save at least 33% and possibly much more raw water (50-75%) depending on the water/air ratio applied. Decreasing the amount of raw water used for cross flushing is attractive especially (i) if raw water costs are high i.e. ground water and (ii) considering that the cross flush water also has to be treated before disposal.

In the case of the horizontal UF module, 82% flux restoration could only be achieved when the water/air ratio was 10:1 or higher (<10% air). At low water/air ratios (33% air) the flux restoration was 40% or lower due to the problem of residual air. The problem was not as apparent when the water/air ratio was increased above 10:1 as the amount of residual air was reduced.

**Hydrodynamic conditions within a hollow fiber during cross flushing**

The maximum flux restoration that could be achieved in a vertical or horizontal UF module after a 15-20 min filtration cycle with surface water was ca. 82% irrespective of whether water alone or a mixture of water/air was used for flushing (Figure 5). However, these results may be valid only for the experimental conditions (turbulent flow) and the surface water employed in this research. In Table 4, a comparison of the hydrodynamic conditions within a vertical and horizontal system are presented for a mean cross flush velocity of 1.63 m/s.

In the horizontal system, the wall shear stress increased from ca. 16 Pa when the system was flushed with water to 130 Pa (shear stress in the liquid film) when 33% air was added to the system. Despite the higher force on the cake layer accumulated at the membrane wall when an air/water cross flush was utilized, the maximum flux restoration that could be achieved in both cases was ca. 82%. The same conclusion can be drawn with respect to the vertical position, i.e. the shear stress in the liquid film was estimated to be ca. 297 Pa for a water/air ratio of 2:1 compared with a wall shear stress of only 16 Pa when water alone was used. Despite the large difference in the shear stress, the flux restoration was 82% in both cases. This phenomenon may be attributed to the fact that the effectiveness of cross flushing is dependent on the mechanism of fouling and the fact that cross flushing is only effective in removing fouling present as a ‘cake layer’ on the membrane surface. Fouling by any other mechanism e.g. complete or standard blocking, is not removed by cross flushing, irrespective of the force applied to the membrane surface.

In Table 5 calculations at a fixed water/air ratio of 10/1 and different mean cross flush velocities in a horizontal system are presented. Increasing the mean velocity increased the wall shear stress of both the liquid slugs and the liquid film, which in theory should improve the flux restoration.

However, the maximum flux restoration achieved in the horizontal position was 82%, despite increasing the cross flush velocity to 1.98 m/s, the shear stress in the liquid film to 20 and the Reynolds number to 2833.
The effect of the filtration mechanism on the cross flushing process

Different cleaning protocols were compared in the treatment of surface water and refinery wastewater (Figure 6) and based on the response of the fouling to the cleaning protocol, various fouling mechanisms were identified (Figure 7). In order to estimate the extent of each fouling mechanism, various cleaning strategies were applied sequentially (in the order listed below), using the most extreme cleaning conditions (pressure, duration and chemical concentration) that the membrane could withstand. After each cleaning protocol was applied (cross flushing, backwashing or chemical cleaning), the extent of flux restoration was estimated from the measurement of the clean water flux. In order to interpret the results, the following assumptions were made:

(i) Cross flushing was assumed to remove only fouling on the membrane surface (cake filtration).

(ii) Backwashing was assumed to remove only fouling deposited (but not adsorbed) within the membrane pores (complete blocking).

(iii) Chemical cleaning was assumed to remove only fouling adsorbed within the pores of the membrane (standard blocking).

In the case of refinery wastewater, 70% of the fouling was removed by cross flushing, 10% by backwashing and 20% by chemical cleaning (Figure 6). From these results it was concluded that 70% of the fouling was due to cake filtration, 10% to complete blocking and 20% to the adsorption of macromolecules, colloids etc. on the surface or within the pores of the membrane.
the membrane (standard blocking) (Figure 7a). The situation with surface water was slightly different as cross flushing removed 80% of the fouling, backwashing 14% and chemical cleaning 6%. Based on these results, the distribution of fouling in the surface water application was 80% cake filtration, 14% pore blocking (complete blocking) and 6% adsorption (standard blocking) (Figure 7b).

In order to improve the efficiency of the cross flushing process, the filtration mechanism must be manipulated such that the particles, colloids, macromolecules etc., in the feed water are too large to enter the pores of the membrane. In this way, cake filtration can be induced from the beginning of the filtration cycle and the extent of blocking filtration can be minimized. If the filtration mechanism can be manipulated to consistently achieve cake filtration, an intermittent cross flush with water and/or water/air should be sufficient to clean UF systems, thus reducing the frequency of backwashing and the consumption of permeate. Moreover, since the presence of the cake layer will also prevent colloids, macromolecules etc. from adsorbing on the membrane surface or on the pore wall, the frequency of chemical cleaning may also be reduced.

It is very unlikely, however, that the need for backwashing and chemical cleaning can be removed completely simply by manipulation of the filtration mechanism because an inherent property of most UF membranes is their pore size distribution. However, the combination of a narrow pore size distribution and manipulation of the filtration mechanism to minimize blocking filtration may help to reduce the consumption of chemicals and permeate and the down time of dead-end UF systems.

Conclusions

- A maximum flux restoration of 70 and 82% was achieved in the case of wastewater and surface water, respectively by cross flushing with water or water/air.
- While the addition of up to 33% air to the cross flush had no beneficial effect on flux restoration in a vertical UF system, it had a strong negative effect on the flux restoration in a horizontal system. The addition of air to the water flush decreased the flux restoration to 40% at high water/air ratios. The low flux restoration in the horizontal system was attributed to residual air in the module after cross flushing.
- While the addition of air to the forward flush increased both the shear stress in the liquid...
film and at the membrane wall in both the vertical and horizontal UF system, the flux restoration of the UF system was not improved.

- In vertical UF systems, the use of air in the cross flushing process can save significant amounts of raw water depending on the water/air ratio applied.
- The success of cross flushing appeared to depend on the filtration mechanism and in particular on the occurrence of cake filtration, which was limited to 70-82% in the two applications investigated.
- In order to improve the efficiency of the cross flushing process, the filtration mechanism must be manipulated so that cake filtration is induced from the beginning of the filtration cycle, thus minimizing the extent of blocking filtration.

References


![Figure 7 Analysis of the fouling mechanism with (a) refinery waste water and (b) surface water](https://iwaponline.com/ws/article-pdf/1/5-6/97/477297/97.pdf)