Application of sequencing batch membrane bioreactors (SB-MBR) for the treatment of municipal wastewater
G. Laera, Bo Jin and A. Lopez

ABSTRACT
Sequencing batch membrane bioreactors can be a good option in up-grading small municipal plant and for industrial applications, maintaining some of the advantages of both original technologies (effluent quality improvement, flexibility and simplicity of realization, operation and control). In this study, the effects of volumetric exchange ratio (VER) and aeration/filtration strategy have been evaluated. Moreover, with the adoption of cycles shorter than 8 h, the opportunity of further simplification of the membrane operation has been tested by choosing a continuous filtration mode instead of the usual short cycle of permeation/relaxation. Two lab-scales MBR equipped with Zenon hollow fiber modules were fed on real primary effluent. For all tests, hydraulic retention time of 10 h and sludge retention time of 60 days have been adopted. Different cycles have been investigated, lasting between 1 and 8 h and all comprising an anoxic phase to allow for denitrification. Operation at low VER resulted in better effluent quality with no limitations to the denitrification phase. For VER > 33% a pre-aeration step was required before effluent withdrawal for optimal ammonium removal. Moreover, VER appeared to have limited negative effect on sludge concentration and yield, while the membrane cleaning frequency slightly increased for increasing VER.

Key words | continuous filtration, membrane bioreactor, nitrogen removal, SBR, volumetric exchange ratio

INTRODUCTION
The application of the membrane bioreactors (MBR) is growing exponentially thanks to several advantages offered by this technology (Judd 2007). It also allows retrofitting and upgrading existing plants in order to increase the treatment capacity and/or to improve the effluent quality, with consequent reduction of the pollutants loading to the receiving aquifer or improved reuse potential for industrial or irrigational purposes.

Among other biological treatments, sequencing batch reactors are sometime preferred in small treatment plants due to their flexibility and simplicity of realization, operation and control. Moreover, in some cases it is required to upgrade small plants originally designed for carbon removal only (i.e., with single activated sludge tank). In all these cases, it can be considered convenient to upgrade and intensify the process by adopting a submerged membrane SB-MBR, avoiding civil works and land use (although increasing the required membrane surface). The application of sequencing batch processes also match well with similar operational mode in some industrial sectors (chemical, pharmaceutical, textile, etc.), with the additional advantage that the effluent quality can be verified prior to discharge. The above considerations justify the increasing interest in the sequencing batch MBRs, as also demonstrated by some recent publication (Bae et al. 2003; McAdam et al. 2005; Scheumann & Kraume 2009).

Early studies on SB-MBR have been focused on the best cycle phase for permeate withdrawal, concluding that it should be done during the aerated phase or soon after (Kang et al. 2003; McAdam et al. 2005). Optimization of the filtration process should also focus on the minimization of the membrane downtime, i.e., the fraction of cycle in which the filtration is not operating, since this parameter directly affect the installation costs. In this regard, one of the aims of this study was to verify the opportunity of starting the filtration phase as soon as the aeration starts in the bioreactor.

From the viewpoint of the biological process, the most appropriate way of feeding and the effect of the hydraulic...
retention time (HRT) have been investigated (McAdam et al. 2005; Scheumann & Kraume 2009). Another important parameter for sequencing biological reactors is the volumetric exchange ratio (VER), i.e., the fraction of reactor volume discharged at the end of each cycle and exchanged with influent wastewater. At constant HRT, the VER is inversely related to the number of cycles per day and, in application with membrane bioreactors, a relatively high number of cycles can be chosen as there are no limitations due to the settling phase. This can turn in better effluent quality but lower conversion rates (Artan et al. 2001; Krampe & Krauth 2001). Indeed, as discussed by Lobos et al. (2008), the number of cycles per day (and so VER) greatly influences the instantaneous values of volumetric and sludge loading rates and this can turn into significant variations of effluent quality and biomass productions. Krampe & Krauth (2001) found that increasing VER in a pilot system fed on municipal wastewater lead to a pronounced increase of the observed yield and poorer nitrogen elimination. However, these results have been obtained under dissimilar operating conditions, since increasing VER corresponded to increasing sludge loading rated and reduced sludge retention time.

This study aims to evaluate the effect of VER and aeration/filtration strategy to reach satisfactory effluent quality while minimizing the membrane downtime. Moreover, with the adoption of cycles shorter than 8 h, the opportunity of further simplification of the membrane operation have been explored by choosing a continuous filtration mode instead of usual short permeation/relaxation cycles. All tests have been done on two lab-scale systems fed on real primary effluent and operated under similar conditions of biomass loading rate, hydraulic and solid retention time.

MATERIALS AND METHODS

Experimental set-up

Two identical lab-scale bioreactors were equipped each with a Zenon hollow fiber membrane module with a surface of 0.047 m² and nominal pore size of 0.1 μm. A schematic diagram of a complete set-up is shown in Figure 1.

A submersible pump was always on to keep the system completely mixed. All other pumps and aerators were controlled by 3 timers that allowed operating the systems in cycles, according to the phases described in Table 1 for five different test conditions adopted. During the last phase (aeration plus filtration), air was pumped at a constant flow through the membrane module (5 L/min) and permeate was continuously sucked up at 17 L/hm². For all the tests, hydraulic retention time of 10 h and sludge retention time of 60 days have been maintained, both calculated considering the average reactor volume.

Methods

Municipal primary effluent was collected 3 times per week from the Glenelg North Treatment Plant (Adelaide, AU).
The detailed characteristics of the wastewater are presented in Table 2.

Chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (N–NH4) and total phosphorus (TP) were measured using analytical kits (Hach, United States), comprising digestion solutions, digestion chamber (Hach DRB 200) and colorimeter (Hach DR890). Nitrite, nitrate and orthophosphate were measured by ion exchange liquid chromatography, using a HPLC pump (Varian ProStar) equipped with a C5 column (Varian), auto sampler (Varian 400) and refractory index detector (Varian 390 RI). Potassium phthalate 4 mM in water was used as mobile phase at 1.5 mL/min.

**RESULTS AND DISCUSSION**

Two identical lab-scale sequencing batch membrane bioreactors have been run in parallel and the effects of different VER and aeration/filtration strategy have been evaluated. The adopted test conditions are reported in Table 1.

The quality of the municipal primary effluent fed to the systems has had no significant variation during the whole experimental campaign and an average volumetric load of 0.50 gCOD/L reactor has been maintained. As reported in Table 3, the COD removal was higher than 85% for all the tests with average effluent concentrations between 20 and 30 mg/L.

The nitrification efficiency was always higher than 96%. However, as shown in Figure 2, when the membrane filtration started with the biomass aeration (tests I–III), the average effluent ammonium concentration was found to be proportional to VER. Ammonium concentration higher than 2 mgN/L could be estimated for VER of 57%, therefore the adoption of a pre-aeration step was preferred (Table 1): tests IV and V showed that, when the filtration was preceded by a 25% of aeration time, the average effluent ammonium concentration resulted as low as 0.4 mgN/L (Table 3).

When considering the denitrification efficiency, it is noteworthy to recall that for increasing VER an increasing amount of nitrate is discharged with the permeate and so it is not available for the following denitrification phase. Therefore, lower VER usually result in better effluent quality. Differently from conventional SBR, in SB-MBR there are no lower limits to the VER as there are no constraints.

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**Table 1 | Operating conditions for the sequencing batch MBR**

<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding + Anoxic</td>
<td>6'</td>
<td>12'</td>
<td>15'</td>
<td>15'</td>
<td>12'</td>
</tr>
<tr>
<td>Anoxic</td>
<td>24'</td>
<td>48'</td>
<td>105'</td>
<td>165'</td>
<td>53'</td>
</tr>
<tr>
<td>Pre-aeration</td>
<td>60'</td>
<td>15'</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aeration + filtration</td>
<td>30'</td>
<td>60'</td>
<td>120'</td>
<td>240'</td>
<td>60'</td>
</tr>
<tr>
<td>No. of cycles per day</td>
<td>24</td>
<td>12</td>
<td>6</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Vol. exchange ratio (%)</td>
<td>9.5</td>
<td>18.2</td>
<td>33.3</td>
<td>57.1</td>
<td>18.2</td>
</tr>
</tbody>
</table>

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**Table 2 | Influent characteristics (all in mg/L)**

<table>
<thead>
<tr>
<th></th>
<th>COD</th>
<th>TSS</th>
<th>TN</th>
<th>N–NH4</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>210</td>
<td>18</td>
<td>49</td>
<td>43</td>
<td>6.9</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>70</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>1.3</td>
</tr>
<tr>
<td>Min</td>
<td>147</td>
<td>13</td>
<td>28</td>
<td>25</td>
<td>3.1</td>
</tr>
<tr>
<td>Max</td>
<td>416</td>
<td>30</td>
<td>61</td>
<td>60</td>
<td>9.5</td>
</tr>
</tbody>
</table>

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**Table 3 | Average effluent and biomass characteristics for different tests**

<table>
<thead>
<tr>
<th>VER %</th>
<th>CODeff mg/L</th>
<th>CODremoval %</th>
<th>NH4–Neff mg/L</th>
<th>NO3–Neff mg/L</th>
<th>Nremoval %</th>
<th>TPeff mg/L</th>
<th>Premoval %</th>
<th>MLVSS g/L</th>
<th>MLVSS/MLSS %</th>
<th>Biomass yield gVSS/gCODrem</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>23</td>
<td>89</td>
<td>0.6</td>
<td>29</td>
<td>38</td>
<td>6.1</td>
<td>10</td>
<td>2.4</td>
<td>85</td>
<td>0.088</td>
</tr>
<tr>
<td>18.2</td>
<td>30</td>
<td>85</td>
<td>1.1</td>
<td>30</td>
<td>38</td>
<td>6.0</td>
<td>7</td>
<td>2.46</td>
<td>87.5</td>
<td>0.097</td>
</tr>
<tr>
<td>33.3</td>
<td>29</td>
<td>86</td>
<td>1.6</td>
<td>27</td>
<td>44</td>
<td>6.0</td>
<td>7</td>
<td>2.29</td>
<td>87.7</td>
<td>0.093</td>
</tr>
<tr>
<td>57.1</td>
<td>21</td>
<td>90</td>
<td>0.4</td>
<td>30</td>
<td>46</td>
<td>5.6</td>
<td>8</td>
<td>2.31</td>
<td>86.0</td>
<td>0.085</td>
</tr>
<tr>
<td>18.2</td>
<td>30</td>
<td>86</td>
<td>0.4</td>
<td>30</td>
<td>36</td>
<td>6.3</td>
<td>8</td>
<td>2.5</td>
<td>88.1</td>
<td>0.091</td>
</tr>
</tbody>
</table>

*a*After molasses feeding.

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**Figure 2 | Ammonium removal and average effluent concentrations for increasing VER.**

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arising from the sludge settling process and VER can be reduced as desired, in order to maximize the effluent quality. However, lower VER also means poorer anoxic conditions and lower substrates concentration with consequent lower conversion rates, therefore an optimum VER must exist. In this study, nitrate removal was always found around 40%, with only a negligible increase of the denitrification efficiency for increasing VER, i.e., for increasing duration of the anoxic phase in tests I to III. These results suggest that there were no limitations due to low conversion rates or lack of proper anoxic conditions, and that the limited denitrification could be ascribed to the insufficient amount of easily biodegradable COD, as also experienced at the treatment plant were the wastewater was collected. As shown in Figure 3, during the final optimized test (run V), the addition of stoichiometric COD as molasses resulted in significantly lower effluent nitrate concentrations, with nitrate removal higher than 80% (Table 3).

Phosphorus removal has been found around 10% for all tests, comparable with the amount needed for the biomass growth and discharged with the excess sludge.

The biomass growth resulted very low, with average yields around 0.09 gVSS/gCODremoved. This value is comparable or even lower than the value found for a similar system operating in continuous mode (Pollice et al. 2008a). Moreover, as reported in Table 3, a slight decreasing trend of biomass concentration and biomass yield was found for increasing VER. This may be explained considering that for increasing exchange ratios the biomass experienced longer periods both in anoxic conditions and in aerated endogenous conditions (towards the end of the filtration period). As a consequence of these conditions of stress, the biomass decay rate slightly increased leading to lower sludge concentration and MLVSS/MLSS ratio.

Regarding the membrane filtration process, instead of a typical filtration/relax operation with duration in the range of 8–12 min/1–2 min (Judd 2006), a simplified operating schedule has been adopted consisting of continuous filtration during the whole aeration/filtration step (Table 1) followed by relaxation during the anoxic phase (and pre-aeration step in tests IV and V). This operation mode was aimed at minimizing the membrane downtime while simplifying the system operation and control. Although a worsening of the filtration performances can be expected, recent studies demonstrated that the applied instantaneous flux has a major role in membrane fouling, i.e., better performance can be obtained with higher interval between two consecutive relaxations and lower membrane downtime (Wu et al. 2008a). Moreover, the biomass reversible fouling deposited on the membrane in early stages of the filtration step can help in preventing long term irreversible fouling (Metzger et al. 2007; Wu et al. 2008b). Differently from these studies (based on short term filtration tests), in this work the applied conditions have been maintained for at least 3 months of operation and the membrane have been cleaned on-site with pressurized tap water whenever the TMP exceeded 50 kPa (no backwashing or chemical cleaning). As shown in Figure 4, the transmembrane pressure (TMP) profile during cycles of different length always followed the mechanism proposed by Metzger et al. (2007) for continuous operation modes: a rapid TMP increase due to fouling by small particles, followed by a long period of low fouling rate due to the formation of a porous cake layer that prevents further pore blocking. It seems that, within the tested range (1–4 h), this mechanism acts independently of cycle duration and membrane status. However, the extent of the initial TMP rise depends on the membrane fouling history. This can be observed in

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**Figure 3** | Influent total nitrogen and effluent nitrate during the final run (test V).

**Figure 4** | Examples of transmembrane pressure monitoring during different SB-MBR cycles.
Figure 4, comparing the two curves for \( t_{\text{filtration}} = 1 \) h, obtained with new membrane and after 6 months of operations.

The average daily TMP increase, measured after each membrane washing event, resulted to be only slightly influenced by the length of the filtration step, with 5–15% increase when passing from 1 to 4 h of continuous filtration. The resulting cleaning frequencies were about 1 washing per month with new membranes and were doubled after 6 month of operation. In comparison with a previous investigation on similar lab-scale systems operating with a typical filtration/backwash mode (Pollice et al. 2008b), the cleaning frequency for the studied SB-MBR resulted to be 2–5 times higher. This could be attributed either to different filtration modes and possibly different aeration intensity or to the presence of an anoxic phase, which could have resulted in higher production of foulant compounds. However, although the results on the filtration performance can be useful to understand the fouling mechanism, the extent of the fouling intensity should only be assessed on full scale membrane modules operated under similar hydrodynamic conditions. It is reasonable to expect better performances for a full scale system with optimized aeration and scouring of the hollow fiber membrane.

**CONCLUSIONS**

Two lab-scales SB-MBR for the treatment of municipal primary effluent have been operated for more than 8 months, under similar conditions except for volumetric exchange ratio and pre-aeration step.

It has been shown that operation at very low exchange ratios was feasible and led to better nitrogen removal (in terms of both effluent ammonium and denitrification efficiency) without worsening of the COD removal. With higher exchange ratios satisfactory ammonium removal could be obtained if a pre-aeration step of 25% of the aeration/filtration time was allowed.

In terms of biomass growth and excess sludge production, the average yields observed for the adopted conditions have been similar to that obtained in continuous system operated under the same conditions. For increasing exchange ratios a slight decrease of the biomass production has been observed.

The filtration performances of the studied systems were directly affected by volumetric exchange ratio due to the adoption of continuous filtration mode during the aeration step and membrane relaxation during the feeding and anoxic steps. In these operating conditions, only a slight worsening of the performances has been observed for increasing exchange ratios, while a more pronounced effect has been observed with the membrane ageing.

The study demonstrated that the volumetric exchange ratio mainly affects the nitrogen removal efficiency, but the SB-MBR system offers a great flexibility and the operator can easily manage to obtain the desired effluent quality with negligible effects on biomass yield and filtration performances.

**REFERENCES**


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