Theoretical analysis and enhanced nitrogen removal performance of step-feed SBR

Jianhua Guo, Yongzhen Peng, Qing Yang, Shuying Wang, Ying Chen and Chenhong Zhao

ABSTRACT

To achieve high nitrification and denitrification rates, step-feed SBR with multiple aerobic and anoxic phases was adopted to study nitrogen removal performance. Theoretical analysis of step-feed SBR was presented first, from which feeding steps and C/N ratio had significant influences on nitrogen removal performance. Total nitrogen removal efficiency would increase with increasing of feeding steps, while the increasing extent was not distinct with feeding steps above 4. At a given feeding step, nitrogen removal efficiency would also increase with increasing of C/N ratio. Experimental work was conducted in a lab-scale SBR to investigate practical effects of these critical factors, using real municipal wastewater. The results showed when C/N ratio was appropriately decreasing influent flow mode could achieve enhanced nitrogen removal with less adding of external carbon source, compared with equal influent flow mode. Three-step equal influent flow mode was recommended to treat common municipal wastewater in view of operation complexity. Non steady-state experiments over about three months confirmed step-feed SBR was an enhanced nitrogen removal process with high efficiency. Total nitrogen in the effluent was under 2 mg/L, the average removal efficiency achieved for TN was over 97% just adding a little external carbon source, and good sludge settleability was obtained.

Key words | biological nitrogen removal, feeding steps, optimal operation, SBR, step-feed, step ratio

INTRODUCTION

As more stringent effluent quality standards are imposed, advanced and cost effective techniques for nitrogen removal from wastewater become more and more important. Many modifications and novel processes have been developed and implemented for nitrogen removal from wastewater (Tchobanoglous et al. 2003). Recently SBRs, as alternative to conventional treatment techniques, have been employed to remove nitrogen in many WWTPs, based on the fact that SBR can carry out biological nitrogen removal in a single reactor by maintaining aerobic and anoxic stages sequentially (Irvine & Ketchum 1988; Andreottola et al. 2001; Wilderer et al. 2001; Akin & Ugurlu 2005). However, the complete removal of nitrogen from wastewaters with low C/N ratio is often limited by lack of available organic carbon source in the anoxic phase to sustain high denitrification rate (Chang & Hao 1996). Consequently, it is common practice to introduce an external organic carbon source in the anoxic phase, leading thus to an increase in the operational cost of the plant (Tam et al. 1992).

In order to achieve high nitrification and denitrification rates, a new operation mode of SBR, step-feed SBR with multiple feed and aerobic and anoxic phases, is applied for enhanced nitrogen removal. As well as the advantages of the typical SBR, step-feed SBR can make good use of influent COD as carbon source required in denitrification process. This means that, by step feeding and multiple aerobic/anoxic
phases, the carbon source required to denitrify nitrite and nitrate formed in each aerobic period is provided by the subsequent anoxic period influent. Moreover, step-feed strategy allows nitrification to occur under a lower organic loading in the aerobic periods, which estimates the inhibition of high organic loading on autotrophic nitrifiers and saves aeration consumptions to oxidize these organic matters. Some studies have been documented in literature on multiple aerobic/anoxic or step-feed in SBR (Lin & Jing 2001; Kargi & Uygur 2002, 2003; Katsogiannis et al. 2003; Puig et al. 2004). However, there were some aspects needed to further upgrade for these studies, such as only a single-feed being available, or aerobic and anoxic durations were fixed, or influent flow fed during the anoxic phases was constant and equal. How to accomplish optimal operation of step-feed SBR would be beneficial for further wide application of this process.

Given the few papers paying attention to theoretical evaluation and analysis of this operation mode, the objectives of this study are to analyse theoretically effects of feeding steps, C/N ratio and influent flow distribution on nitrogen removal, and deduce nitrogen removal efficiency. Moreover, practical effects of these factors and nitrogen removal performance were investigated in step-feed SBR with real municipal wastewater in order to provide useful information to optimal operation of step-feed SBR.

MATERIALS AND METHODS

Experimental set-up

A schematic diagram of experimental equipment is shown in Figure 1. The reactor was made of acrylic fibre plastics with a working volume of 15 L. Compressed air was used for aeration. A mechanical stirrer was used to provide liquid mixing when the air compressor stopped working. In addition, the pH, ORP and DO sensors were installed for monitoring pH, ORP and DO in the reactor. Samples were collected at intervals according to DO, pH and ORP variations.

Analytical methods

Temperature and pH were detected on line using WTW level 2 pH probe. ORP and DO were continuous monitored by WTW, pH/oxi340i meter with ORP and DO probes, respectively. COD, NH$_4^+$-N, NO$_2^-$-N, NO$_3^-$-N, TN and MLSS (mixed liquid suspended solid concentration) were measured according to Standard Methods (APHA 1995).

Wastewater and seed sludge

The influent used in the lab-scale SBR was real municipal wastewater taken from a primary sedimentation tank of a WWTP (Beijing, China). The seeding sludge with a mixture of heterotrophic organisms capable of oxidizing carbonaceous compounds and denitrification and autotrophic nitrifying organisms was obtained from Qinghe WWTP (Beijing, China). The characteristics of influent are listed in Table 1. COD$_r$ and NH$_4^+$-N in the raw wastewater was 180–220 mg/L and 40–60 mg/L, respectively. MLSS was

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
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<tbody>
<tr>
<td>COD</td>
<td>180–220 mg/L</td>
</tr>
<tr>
<td>NH$_4^+$-N</td>
<td>40–60 mg/L</td>
</tr>
<tr>
<td>NO$_2^-$-N</td>
<td>0.2–0.8 mg/L</td>
</tr>
<tr>
<td>NO$_3^-$-N</td>
<td>0.2–1.2 mg/L</td>
</tr>
<tr>
<td>TKN</td>
<td>50–70 mg/L</td>
</tr>
<tr>
<td>Temperature</td>
<td>28 ± 1°C</td>
</tr>
<tr>
<td>pH</td>
<td>6.5–8.0</td>
</tr>
</tbody>
</table>
3,000–3,500 mg/L. After the cultivation of the activated sludge, the experiment lasted for 6 months.

Operation strategy

Figure 2 shows the operation strategy of two and three steps feed SBR. For three-step SBR, there were three fill phases, which were achieved in very short time, just like pulse filling. There were three aerobic-anoxic combinations and at the last anoxic phase, external carbon source (95% ethanol) was added in the reactor as electron donor for denitrification. In view of satisfying the standards of Beijing Olympic Lake supplement water (TN ≤ 2 mg/L), a little dosage of external carbon source is introduced, although leading to an appreciable increase in the operational cost. During the draw phase, the clarified supernatant was withdrawn. Both anoxic and aerobic durations were not fixed but distributed by real-time control using pH as control parameter (Guo et al. 2007). Settle and draw phases were fixed, about 30 and 45 min durations, respectively. The operation strategy of two-step feed SBR is similar with three-step except with two fill phases and two aerobic-anoxic combinations.

THEORETICAL ANALYSIS OF STEP-FEED SBR

Process modeling and assumptions

In order to discuss conveniently, the following assumptions are introduced. Denitrification is developed until either of nitrate or carbon source concentration becomes zero in anoxic phase. And nitrification is progressed until either of ammonia or alkalinity becomes zero in aerobic phase. The amounts of ammonia by assimilation and nitrate in influent are negligible. In theory, it has been established that, under anoxic conditions with biodegradable organic substrate present, the COD consumption is 2.86/(1 – $Y_H$) mg to reduce 1 mg N-nitrate (Ekama & Marais 1984; Gujer et al. 1996). Here $Y_H$, as anoxic biomass yield coefficient (mg CODbiomass/mg CODsubstrate), is a constant parameter. In ASM 3, $Y_H$ is assumed to be 0.54 (Gujer et al. 1996), correspondingly COD consumption is 6.22 mg to reduce 1 mg N-nitrate into nitrogen gas. Conveniently, in practice the value of COD required to reduce 1 mg NO$_3^-$ – N can be defined as $k$ mg. Besides, influent COD/TN ratio is set to be $x$.

Formulation of nitrogen removal efficiency

Unequal feed flow mode

To ensure the nitrate formed in first aerobic phase denitrifies completely, the amount of carbon source provided by the influent of the subsequent fill phase should be $k$ times the nitrate amount. Here, TN in the first step feed is set to be $a$. By deducing theoretically the relationship of feeding step and influent COD/TN ratio, nitrogen removal efficiency ($\eta$) can be denoted as shown in Table 2. If $x > k$, nitrogen removal efficiency would increase with increasing of feeding steps and tend to 100% with feeding steps tending to $n$. Besides, the influent flow is decreasing in turn as feeding steps increase, defined as decreasing influent flow fill mode. If $x < k$, nitrogen removal efficiency would increase with increasing of feeding steps and tend to $x/k$ with feeding steps tending to $n$. However, the influent flow is increasing in turn with feeding steps increasing, defined as increasing influent flow fill mode. For unequal feed flow mode, it can be found that if the amount of carbon source provided by the influent of the subsequent feed phase is $k$ times of the nitrate amount, then all COD contained in each step influent would be used to denitrify and more aeration consumption would be saved.

From the following formulation (1),

$$\eta = \left(\frac{y_1}{x} - \frac{(k/x)^{n-1}}{x} \right) \left(\frac{y_1 - (k/x)^{n}}{x} \right)$$

it can be found that nitrogen removal efficiency is the function of feeding steps ($n$) and influent C/N ratio ($x$). Figure 3 shows the function relationship of nitrogen removal efficiency and feeding steps and C/N ratio ($k$ in the
formulation (1) is set to be 6.22). It can be observed that total nitrogen removal efficiency would increase with increasing of feeding steps, while the increasing extent was not distinct with feeding steps above 4. At a given feeding steps, nitrogen removal efficiency would also increase as increasing C/N ratio.

Particularly, the relationship of between nitrogen removal efficiency and C/N ratio was described as Figure 4 under feeding steps of 2, 3 and 4. From Figure 4, nitrogen removal efficiencies in theory under feeding steps to be 2, 3 and 4 were 53%, 71% and 79% with C/N of 7, respectively.

If complete nitrogen removal is expected, external carbon source can be introduced in the last anoxic phase and the dosage external carbon source would be reduced as increasing of feeding steps. However, increasing of feeding steps implies operation complexity. Consequently, many more feeding steps were not recommended in practice.

Equal feed flow mode

The assumptions for equal feed mode are as same as in unequal feed flow mode. Compared with unequal feed flow mode, the influent flow of every fill phase is same and the TKN amount included in every influent equals to a. The relationship of feeding steps and COD/TN ratio and nitrogen removal efficiency is given in Table 3. Similarly, nitrogen removal efficiency would be improved by increasing of feeding steps.

RESULTS AND DISCUSSION

From theoretical analysis aforementioned, feeding steps and C/N ratio had significant influences on nitrogen removal efficiency. In order to study practical effects of these factors on nitrogen removal, experimental works was conducted in the lab-scale SBR using real municipal wastewater. Moreover, nitrogen removal performance was investigated only

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Table 2 | Nitrogen removal efficiency formula of unequal feed flow mode

<table>
<thead>
<tr>
<th>Feeding steps (n)</th>
<th>(\eta) value (when (x = k))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\eta = 0/a)</td>
</tr>
<tr>
<td>2</td>
<td>(\eta = a/(a + ka/x))</td>
</tr>
<tr>
<td>3</td>
<td>(\eta = (a + ka/x)(\gamma a + ka/x + (kix)^{2}-a)/f)</td>
</tr>
<tr>
<td>4</td>
<td>(\eta = (\gamma a + ka/x + (kix)^{2}-a)/\gamma a + ka/x + (kix)^{2}-a + (kix)^{3}/f)</td>
</tr>
<tr>
<td>…</td>
<td>(\eta = (\gamma 1 - (kix)^{n-1} - (kix)/f))</td>
</tr>
</tbody>
</table>

Figure 3 | Relationship of theoretical nitrogen removal efficiency and C/N and feeding steps.

Figure 4 | Relationship of theoretical nitrogen removal efficiency and C/N and feeding steps.
in two and three steps feed SBR, in view of more complicated operation and less contribution to nitrogen removal efficiency while feeding steps above 4.

Nitrogen removal performance in equal feed flow SBR

For two-step equal feed mode, every influent flow was 5 L and three-step equal feed mode was 3 L.

As shown in Figure 5, every aerobic phase nitrification proceeded completely, the ammonia concentration was lower than 2 mg/L. Denitrification was also complete, the nitrate concentration was almost negligible. At the last anoxic period, total nitrogen in effluent was lower than 2 mg/L when adding 0.8 and 0.5 mL 95% ethanol, which was attained by in preliminary experiment. The duration of oxic 2 was shorter than oxic 1 for the reason that most COD in the second influent were utilized as electron donors, which could avoid the negative impact of organic loading on nitrification. Moreover, denitrification rates were fast and accepted, where every fill flow was equal.

In Figure 5a it can be seen that NO$_3^-$-N concentration decreased from 28.14 to 0.5 mg/L during 60 min duration of anoxic1. In two-step and three-step equal feed SBR, carbon source required in denitrification could be provided sufficiently with COD contained in the influent with C/N of 3.5. Strictly speaking, there were surplus COD in the end of anoxic phases. Consequently, it was necessary to investigate the performance of operation with decreasing influent flow, but it was not necessary to investigate the performance with increasing influent flow.

Nitrogen removal performance in decreasing feed flow SBR

For wastewater with C/N of 3.5 used in this study, step ratio was 1.5, which was obtained form previous study (Guo et al. 2007). When the step ratio was fixed at 1.5, almost all of biodegradable COD contained in each step influent would be utilized to denitrify nitrite and nitrate as electron donors. Based on it, for two-step decreasing feed mode, every influent flow was 6 and 4 L, respectively. Correspondingly, three-step decreasing fill mode, every influent flow was 4.5, 3 and 2 L, respectively. Nitrogen removal performance in decreasing feed SBR is shown in Figure 6.

From Figure 6a, b, it can be observed that every aerobic phase nitrification proceeded completely, as well as denitrification in every anoxic phase. Furthermore, it should be noted that the ethanol dosage can be saved, just adding 0.6 and 0.3 mL, compared with equal feed flow mode. For unequal fill flow mode in this study, the amount of carbon source provided by the subsequent anoxic period influent could ensure nitrate amount formed be denitrified completely. Most COD contained in each step influent would be used to denitrify, but not to be degraded by

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**Table 3 | Nitrogen removal efficiency formula of equal feed flow mode**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Nitrogen removal efficiency formula (η)</th>
<th>η value (when n → ∞)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x &gt; k</td>
<td>η = (n - 1)α/nα = (n - 1)/n</td>
<td>1</td>
</tr>
<tr>
<td>x &lt; k</td>
<td>η = (n - 1)/(αx)/k/nα = (n - 1)x/k</td>
<td>x/k</td>
</tr>
</tbody>
</table>

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**Figure 5 | Nitrogen removal performance in equal feed flow mode (a: two-step; b: three-step).**
aeration, leading to save aeration consumption to oxidize these organic matters. Moreover, nitrification in following aerobic phase could occur under a lower organic loading in the aerobic periods, which estimated the inhibition of high organic loading on autotrophic nitrifiers. Consequently, decreasing fill mode would be optimal operation under C/N was appropriated, which implied reducing carbon source dosage and lead to saving aeration consumptions.

**Effect of step ratio on nitrogen removal in two-step SBR**

Step ratio ($\lambda_i$) is defined as follows: $\lambda_i = Q_i/Q_i + 1$, $Q_i$ is the $i$ time influent flow. According to the fact that step ratio is quite a significant parameter to step-feed SBR, its effect on nitrogen removal performance was investigated in two-step feed SBR. By adding a small volume of soybean wastewater into municipal wastewater, C/N ratio was increased to be 7.5 on purposely and then nitrogen removal performance was compared under different step ratio. Table 4 shows the effects of step ratio on operation performance. It can be concluded that ethanol dosage were gradually reduced with increasing step ratio, for the reason that effluent NO$_2^-$-N concentrations without ethanol dosage were gradually decreasing. Specific nitrification rate $I$ was gradually reduced with increasing step ratio due to the amount of ammonia gradually decreasing. Besides, it should be noted specific denitrification rates of anoxic 1 were also gradually reduced with increasing step ratio, which was contributed to the amount of carbon source provided by the influent of

![Figure 6](image.png)  
**Figure 6** Nitrogen removal performance in decreasing feed flow mode (a: two-step; b: three-step).

<table>
<thead>
<tr>
<th>Item</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step ratio</td>
<td>1.50</td>
<td>1.86</td>
<td>2.33</td>
</tr>
<tr>
<td>Fill mode(L)</td>
<td>6.0 + 4.0</td>
<td>6.5 + 3.5</td>
<td>7.0 + 3.0</td>
</tr>
<tr>
<td>Influent C/N ratio</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Effluent NO$_2^-$-N without ethanol dosage (mg/L)</td>
<td>13.5</td>
<td>10.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Ethanol dosage (mL)</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Specific nitrification rate $I$ [mg NH$_4^+$-N/(g MLSS·min)]</td>
<td>0.1213</td>
<td>0.1076</td>
<td>0.1012</td>
</tr>
<tr>
<td>Specific denitrification rate $I$ [mg NO$_2^-$-N/(g MLSS·min)]</td>
<td>0.1359</td>
<td>0.1255</td>
<td>0.1256</td>
</tr>
<tr>
<td>Specific nitrification rate $II$ [mg NH$_4^+$-N/(g MLSS·min)]</td>
<td>0.1218</td>
<td>0.1108</td>
<td>0.1132</td>
</tr>
<tr>
<td>Specific denitrification rate $II$ [mg NO$_2^-$-N/(g MLSS·min)]</td>
<td>0.1433</td>
<td>0.1257</td>
<td>0.1376</td>
</tr>
</tbody>
</table>
the second feed phase was gradually reducing. For the wastewater with given C/N ratio there would be a unique and optimum step ratio, which can be obtained by optimization experiments by considering both from denitrification rates and external carbon source dosage. Nitrification and denitrification rates were higher in this study, which is benefited from distributing and regulating accurately aeration and anoxic duration by real-time control.

Non steady-state experiments

For step-feed SBR, one of the major drawbacks is it is too difficult to distribute appropriately aerobic and anoxic durations. In this study aerobic and anoxic durations were controlled by real-time control system using pH and ORP as control parameters, which could determine flexibly each aerobic and anoxic hydraulic retention time (HRT) to ensure nitrification and denitrification proceeded completely (Guo et al. 2007). Based on the regulations and control strategy, non steady-state experiment with variable influent wastewater characteristics was conducted (Figure 7).

The results showed nitrogen removal efficiency of higher than 97% could be obtained in step-feed SBR. Effluent total nitrogen concentrations were all below 2 mg/L during non steady-state periods.

Besides, sludge settleability was ideal and SVI was lower than 100 mL/g. Based on non steady-state experiments it was confirmed that step-feed SBR was an enhanced nitrogen removal process with high efficiency and robust capacity of anti sharp loading.

CONCLUSIONS

Theoretical analysis of step-feed SBR was given and the practical effects of critical factors (including feeding steps, influent flow distribution and C/N ratio) on nitrogen removal performance were discussed in the study.

- Based on theoretical evaluation and analysis, total nitrogen removal efficiency would increase with increasing of feeding steps, while increasing extent was not distinct with feeding steps above 4. At a given feeding steps, nitrogen removal efficiency would increase as increasing of C/N ratio.
- When C/N ratio was appropriate or high decreasing influent flow mode could achieve enhanced nitrogen removal with adding less external carbon source, compared with equal influent flow mode. Three-step equal influent flow mode was recommended to treat common municipal wastewater in view of operation complexity.
- The step-feed SBR was confirmed to be an enhanced nitrogen removal process, with treated effluent TN less than 2 mg/L and average TN removal efficiency over 97%, while only limited external carbon source was required.

ACKNOWLEDGEMENTS

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