Operation for nitritation of sludge liquor in a full-scale SBR
D. J. I. Gustavsson, U. Nyberg and J. La Cour Jansen

ABSTRACT
At Sjölanda WWTP, a full-scale SBR for treatment of mesophilic sludge digester liquor has been operated almost a year with stable nitrite accumulation. Only nitritation of the sludge liquor is needed since the oxidized ammonium is denitrified in the first anoxic zone of the high-loaded activated sludge in the main plant. The process strategy was to have an ammonium set-point to end the aeration, a low DO concentration and a low pH set-point. An increase of pH set-point from 6.8 to 7.2 increased loss of alkalinity in the effluent and increased sodium hydroxide dosing. An increase of DO set-point from 1.1 mg O2 L\(^{-1}\) to 1.3 mg O2 L\(^{-1}\) markedly increased ammonia reduction rates and only slightly increased nitrate production. Today, an introduction of denitritation in the SBR will be a more cost-effective treatment of sludge liquor at Sjölanda WWTP. However, the choice of operation with only nitritation or nitritation/denitritation in sludge liquor treatment should always include a consideration of chemical costs and treatment capacity of both main plant and side-stream plant.

Key words | full-scale, nitritation, nitrite accumulation, sludge liquor

INTRODUCTION
At Sjölanda WWTP in Malmö, Sweden, a full-scale sequencing batch reactor (SBR) for treatment of mesophilic sludge digester liquor has been operated almost a year with stable nitrite accumulation. Only nitritation of the sludge liquor is needed since the treated sludge liquor enters the main plant in the sand traps at the head of the plant and the oxidized ammonium is denitrified in the first anoxic zone of the high-loaded activated sludge plant. Nitrogen removal in the main stream is applied by nitrification in trickling filters and by high rate post-denitrification in moving-bed biological reactors with addition of methanol as carbon source (Hanner et al. 2003). Figure 1 shows the treatment plant configuration at Sjölanda. The nitrifying capacity in the main plant is limited during at least eight months a year. During summer nitrifying activity in the high-loaded activated sludge plant and higher nitrifying capacity in the trickling filters is sufficient and the SBR is closed down in order to minimize operational costs. The fast start-up procedure of the SBR with only nitritation is described in Gustavsson et al. (2007) which also includes a detailed description of the SBR.

Denitritation of the sludge liquor is not needed to secure sufficient nitrogen removal but could be a cheaper way for alkalinity supply than the present dosing of sodium hydroxide, however, other benefits and draw backs have to be considered to judge the best treatment option. The objectives of this study were to evaluate the successful operation of one year with nitrite accumulation in the SBR and to make an operational and economical evaluation of introducing denitritation in the SBR operation at Sjölanda WWTP.

METHOD
The SBR at Sjölanda WWTP has an operating volume of 1,500–2,000 m\(^3\). The minimum volume is restricted by the level of the decantation pipes. Two equalisation tanks are
available to equalise untreated sludge liquor and treated liquor. The SBR is operated in four cycles per day (360 minutes each). Each cycle consists of an aeration phase with simultaneous mixing and filling, a settling phase and a withdrawal phase. Each phase has a pre-set time. The aeration can be extended with a second aeration phase without filling. Figure 2 shows a typical cycle with the different phases. The sludge liquor is fed at a constant flow rate (about 60 m$^3$h$^{-1}$). Surplus sludge is withdrawn during aeration when necessary. Dosing of sodium hydroxide is possible during the aeration phase. The following on-line instruments are used for supervision and control. Temperature and pH: OrbiPac CPF81 (Endress + Hauser), dissolved oxygen (DO): LDO (Hach Lange), mixed liquor suspended solids (MLSS): Solitax ts-line sc (Hach Lange) and ammonium nitrogen: VARION AN/A comp SET (WTW). The aeration system used is fine bubble membrane disc diffusers (Sanitaire) which are even distributed on the bottom of the SBR.

A 24-hour composite sample of the influent was taken daily. Grab samples of the effluent and the SBR during aeration were taken daily during working days. Ammonium, nitrite, the sum of nitrite and nitrate ($\text{NO}_x^-\text{N}$) and total nitrogen were analysed colorimetrically after filtration using a flow injection analyser (FIAstar 5000). Samples for total nitrogen were first digested with peroxodisulphate. Suspended solids (SS) were quantified with Munktell MGA filter paper with pore size 1.6 µm. The same type of filter paper was used for all filtrated samples. Volatile suspended solids (VSS) were determined after calcination in a muffle furnace at 550°C for at least two hours. Volatile fatty acids (VFA) were measured according to VAV (1984). All analyses except the VFA analysis follow Swedish standard methods.

**OPERATIONAL STRATEGIES**

The process strategy to accumulate nitrite is to suppress nitrite oxidisers and to favour ammonia oxidisers. Firstly, the high temperature of the sludge digester liquors favours ammonia oxidisers which grow twice as fast as nitrite oxidisers at 35°C (Hellinga et al. 1998). The DO set-point was set to be low since ammonia oxidisers have a lower oxygen half saturation constant than nitrite oxidisers (Hanaki et al. 1990). Also the intermediate hydroxylamine ($\text{NH}_2\text{OH}$) in the ammonia oxidation accumulates at low DO concentrations (Yang & Alleman 1992) and hydroxylamine inhibits nitrite oxidisers already at low concentrations (Noophan et al. 2004). However, a low DO concentration lower the ammonia reduction rates since...
the typical half saturation constant for ammonia oxidisers is around 0.5–1.0 mg O₂ L⁻¹ (Henze et al. 2002) and DO concentrations around 1 mg O₂ L⁻¹ increases the risk of substantial dinitrogen oxide production (Tallec et al. 2006). Earlier the DO set-point at the plant has been chosen to 1.8 mg O₂ L⁻¹ or above without getting any stable nitrite accumulation (unpublished results). During this study the DO set-point was 1.1 mg O₂ L⁻¹, except during the last period when the set-point was increased in order to examine the increase in ammonia reduction rates. Secondly, the stress on the nitrite oxidisers can alleviate if the aeration period is too long (Turk & Mavinic 1989). Therefore, the aeration phases were stopped before the pre-set time when a set-point of ammonium concentration was fulfilled. 90% ammonium oxidation (to a level about 70–90 mg NH₄-N L⁻¹) was chosen.

Since sludge digester liquors normally do not have enough alkalinity for the ammonia oxidation, alkalinity has to be added. Mulder et al. (2001) noticed, in full-scale, a 50% decrease in ammonia oxidation when pH dropped below 6.5. Not only the low pH itself inhibits nitrifiers, also high nitrite concentration in combination with low pH lead to excessively high concentration of nitrous acid, suppressing both ammonia and nitrite oxidisers. However, ammonia oxidisers tolerate higher nitrous acid concentration than nitrite oxidisers (Vadivelu et al. 2007). Since the uncharged forms of ammonium (NH₃) and nitrite (HNO₂) are considered to be the actual substrate for their respective oxidiser (e.g. Anthonisen et al. 1976), lower pH ranges favour nitrite oxidisers because nitrous acid concentration increases when lowering pH. Furthermore, higher pH ranges favour ammonia oxidisers since ammonia concentration increases when increasing pH. The choice of a high pH set-point would increase sodium hydroxide dosing. The pH set-point has been chosen to 6.8 as earlier experience has shown that it gives reasonable alkalinity dosing. In this study an increase of the pH set-point was studied to see if higher ammonia reduction rates could be achieved and if minimized hydroxide dosing could be achieved because of less carbon dioxide stripping at higher pH.

In the few cases of problems with reduced ammonia oxidation rate the strategy was to optimise the conditions for ammonia oxidiser as much as possible. DO limitation and ammonia inhibition were avoided as much as possible. The strategy was to extend the aeration period, set the blowers in manual at maximum speed or/and by-pass sludge liquor until the nitritation rates became normal again.

RESULTS AND DISCUSSION

Sludge liquor composition

The SBR was operated for 265 days during the period of late October 2006 until mid-July 2007. Table 1 shows the sludge liquor composition. The average ammonium load after the start-up period (day 17 and forward) was 650 kg NH₄⁺-N d⁻¹. The average sludge liquor flow was 710 m³ d⁻¹. The HCO₃⁻ : NH₄⁺-N molar ratio was at average 1.14. The high standard deviation for the suspended solids (SS) concentration depends on bad sludge liquor quality (>1,000 mg SS/l) during 32 days at 15 occasions. Excluding these days gives an average SS concentration of 430 mg SS/l (SD = 180 mg SS/l).

Nitritation

No problems to maintain stable nitrite accumulation was observed (Figure 3). Nitrite made up the dominating part of the inorganic nitrogen in the effluent. The percentage of nitrate was only 8% at average. During the first 87 days the pH set-point was set to be 0.2 lower in the second phase than in the first aeration phase. This operation strategy was changed during day 88 since the ammonia reduction rate was observed to be lower below pH 6.8. Between day 108 and day 170 the effect of increasing the pH set-point was examined. At day 171 the pH set-point was set to the original set-point of 6.8. At day 182 the DO set-point was increased from 1.1 mg O₂ L⁻¹ to 1.3 mg O₂ L⁻¹. However the DO set-point was not reached due to increased aging of the fine bubble disc membrane diffusers.

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Table 1 | Composition of the sludge digester liquor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Average</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₄⁺-N</td>
<td>mgL⁻¹</td>
<td>910</td>
<td>89</td>
<td>228</td>
</tr>
<tr>
<td>Tot-N</td>
<td>mgL⁻¹</td>
<td>1,010</td>
<td>95</td>
<td>19</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>mgL⁻¹</td>
<td>4,490</td>
<td>370</td>
<td>219</td>
</tr>
<tr>
<td>VFA</td>
<td>mgL⁻¹</td>
<td>46</td>
<td>22</td>
<td>217</td>
</tr>
<tr>
<td>SS</td>
<td>mgL⁻¹</td>
<td>760</td>
<td>1,170</td>
<td>251</td>
</tr>
</tbody>
</table>
and the DO concentration mostly was below 0.6 mg O$_2$ L$^{-1}$. First at day 228, when an extra blower was installed, the new set-point was reached. At day 265, the SBR was taken out of operation for the season.

The operation was very stable during the whole study period with few exceptions. At day 83 an accident shut-down in power resulted in disruption of air flow operation leading to DO concentrations of 0.6 mg O$_2$ L$^{-1}$ which decreased the nitritation rate. The changes in the SCADA-system due to the power shut-down were discovered after a couple of days. At day 151 the pH-electrode crashed forcing the sodium hydroxide dosing to be kept at manual mode. When replacing the electrode five days later the pH had reached 8.9 resulting in inhibition of the ammonia oxidisers. Bad sludge liquor quality increased the energy demand for holding the DO set-point and also decreased the sludge retention time (SRT) since the withdrawal of surplus sludge was manually increased when reaching too high MLSS concentrations ($>3,000$ mg MLSS L$^{-1}$). The average SRT during the whole period was 29 days (SD = 28 days). It is also important to point out that the SBR was operated with the actual load and not to the maximal capacity.

During the whole study period, the aerobic hydraulic retention time (HRT) was at average 1.4 days with an average ammonium removal of 91% or 0.65 kg NH$_4^+$-N m$^{-3}$d$^{-1}$ (0.27 g NH$_4^+$-Ng$^{-1}$MLSS d$^{-1}$, 0.41 g NH$_4^+$-Ng$^{-1}$MLVSS d$^{-1}$). The total average HRT was very long (2.3 days), since the nitritation capacity was much higher than the load giving long idle times in form of long sedimentation times. The average exchanged volume per cycle was 11%.

The average power consumption was 2.0 kWh kg$^{-1}$ NH$_4^+$-N removed following the air consumption of 45.5 Nm$^3$kg$^{-1}$ NH$_4^+$-N removed. The oxygenation efficiency decreased during the period since aging of the fine bubble disc membrane diffusers increased severely. The first 147 days, the power consumption was 1.5 kWh kg$^{-1}$ NH$_4^+$-N compared to the second period which had a consumption of 2.6 kWh kg$^{-1}$ NH$_4^+$-N (70% increase). The sodium hydroxide consumption was 2.4 kg NaOH kg$^{-1}$ NH$_4^+$-N removed, which is equal to 0.84 mol OH$^{-}$ mol$^{-1}$ NH$_4^+$-N removed.

Small flocs with good settling properties and many free-living bacteria characterised the sludge. The MLSS concentration was manually corrected to be low, at average 2,700 mg MLSSL$^{-1}$ (MLVSS MLSS$^{-1}$ = 0.66). Major foaming problems occurred during periods giving an unpleasant working environment. No anti-foaming agents were used.

Increasing the pH set-point stepwise up to 7.2 increased the nitritation rates minimally, but the sodium hydroxide dosing tended to increase and significantly unwanted loss of bicarbonate in the effluent was observed (Table 2). The loss of alkalinity at pH 7.2 corresponds to an increase of sodium hydroxide consumption of about 20% compared to operation at pH 6.8. No bicarbonate limitation at pH 6.8 was observed since the concentration never was below 3 mmolL$^{-1}$, which is the limit for carbon limitation for ammonia oxidisers according to Guisasola et al. (2007).

**Table 2** | The difference in ammonium reduction rate, sodium hydroxide dosing and alkalinity loss at different pH set-points

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>pH 6.8</th>
<th>pH 7.0</th>
<th>pH 7.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_4^+$-N reduction rate</td>
<td>kg NH$_4^+$-Nm$^{-3}$d$^{-1}$</td>
<td>0.57</td>
<td>0.68</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>g NH$_4^+$-Ng$^{-1}$MLSS d$^{-1}$</td>
<td>0.18</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>Dosed OH/reduced NH$_4^+$-N</td>
<td>MmolL$^{-1}$</td>
<td>0.81</td>
<td>0.83</td>
<td>0.93</td>
</tr>
<tr>
<td>HCO$_3^-$ in effluent</td>
<td>MmolL$^{-1}$</td>
<td>6.4</td>
<td>11.2</td>
<td>16.5</td>
</tr>
<tr>
<td>Mold$^{-1}$</td>
<td>4,430</td>
<td>8170</td>
<td>11</td>
<td>11,250</td>
</tr>
</tbody>
</table>

Figure 3 | Effluent concentrations of NH$_4^+$-N, NO$_2^-$-N and NO$_3^-$-N during the study period.
Increasing the DO set-point to 1.3 mg O₂ L⁻¹ increased the nitritation rates with about 25% volumetrically and with about 67% per g MLSS (Table 3). The calculated NO₃⁻-N concentration increased slightly (Figure 4).

**Introduction of denitritation**

Earlier economical evaluations of side-stream treatment of sludge digester liquor, i.e. Fux *et al.* (2003), Fux & Siegrist (2004) and Parravicini *et al.* (2008), has not considered only nitritation as an option. The most economical option was found to be partial nitritation combined with the Anammox process. However, today the Anammox process is not run in many full-scale applications and is not yet totally reliable. The annual close-down at Sjölunda makes Anammox less cost-effective than nitritation/denitritation according to the evaluation principles in Fux & Siegrist (2004). Nitritation and subsequent denitritation requires a suitable carbon source. If limited nitrifying capacity in the main plant is the reason for side-stream treatment, which is the case at Sjölunda WWTP, the main reason for introducing denitritation is to lower the cost to gain alkalinity. Expecting 90% ammonium removal, the chemical costs would decrease strikingly from €560 d⁻¹ with only nitritation to €300 d⁻¹ when adding methanol. However, also operational consequences and capacity of the SBR of introduction of denitritation have to be considered. Operation with only nitritation gives significant denitritation of readily biodegradable organic matter in the main plant, which decreases the total oxygen consumption. Operation with denitritation increases the sludge production and MLSS concentration in the SBR leading to lower nitritation rates and extended need for aeration. Table 4 shows the significant economical consequences of different operational schemes for the SBR with the present operation of the main plant at Sjölunda WWTP. During the coming operational season with denitritation a more detailed economical evaluation will be included. Further, denitritation in the SBR would make it possible to introduce biological phosphorus removal at the plant with potential savings up to €100 d⁻¹ for the present iron sulphate dosage. At the present operation, nitrate recirculation from the NTFs is only performed to one half of the activated sludge plant and the treated sludge liquor is lead to the other half.

Prices of external easily degradable carbon sources as ethanol and methanol will probably rise since there is an increasing interest to use them as fuels. Internal carbon sources, i.e. raw wastewater and hydrolysate, are preferred but are much diluted, decrease the temperature and increase the required volume of the side-stream treatment plant.

**CONCLUSIONS**

- No problems related to the ammonia oxidation process were noticed during operation of a full-scale SBR during almost one year with only nitritation.
- Disturbance of pH controlling equipment was the main disturbance factor for operating the SBR at high nitritation rates.

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**Table 3** | The difference in ammonium reduction rates at different DO set-points

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>1.1</th>
<th>1.3</th>
<th>n</th>
<th>1.1</th>
<th>1.3</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₄⁺-N</td>
<td>kg NH₄⁺-N m⁻³ d⁻¹</td>
<td>0.65</td>
<td>0.81</td>
<td>15</td>
<td>0.81</td>
<td>1.3</td>
<td>80</td>
</tr>
<tr>
<td>reduction rate</td>
<td>G NH₄⁺-N g⁻¹ MLSS d⁻¹</td>
<td>0.24</td>
<td>0.40</td>
<td>9</td>
<td>0.40</td>
<td>1.3</td>
<td>55</td>
</tr>
</tbody>
</table>

**Table 4** | Cost estimate for chemical costs in the SBR and energy savings in the main plant with dosage of NaOH and nitritation/denitritation with dosage with methanol and ethanol respectively

<table>
<thead>
<tr>
<th></th>
<th>Nitritation (NaOH)</th>
<th>Nitritation/denitritation (methanol)</th>
<th>Nitritation/denitritation (ethanol)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SBR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals</td>
<td>0.96</td>
<td>0.51</td>
<td>0.79</td>
</tr>
<tr>
<td><strong>Main plant</strong></td>
<td></td>
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</tr>
<tr>
<td>Energy</td>
<td>−0.15</td>
<td>−0.02</td>
<td>−0.02</td>
</tr>
<tr>
<td>Total costs</td>
<td>0.81</td>
<td>0.49</td>
<td>0.77</td>
</tr>
</tbody>
</table>

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**Figure 4** | The volumetric and MLSS ammonium reduction rate and calculated nitrate concentration during the study period.
Today an introduction of denitrification in the side-stream SBR will be a more cost-effective treatment of sludge liquor at Sjölunda WWTP.

The choice of operation with only nitritation or nitritation/denitrification in sludge liquor treatment should include a consideration of chemical costs and the treatment capacity of both main plant and side-stream plant.

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REFERENCES


APPENDIX

Cost estimate

Chemicals

Nitrification/denitrification: COD consumption: SBR. 2.2 g CODg⁻¹ N denitrified (Fux et al. 2003); main plant; 3.3 g CODg⁻¹ NO₂⁻ N (van Kempen et al. 2001), chemical prices: ethanol (€0.89 kg⁻¹) and methanol (€0.41 kg⁻¹). Nitrification: Sodium hydroxide consumption: 2.4 kg NaOH kg⁻¹ NH₄⁺ removed, chemical price: NaOH (€0.40 kg⁻¹).

Energy costs in main plant

Oxygenation efficiency: 1.7 kg O₂ kJ⁻¹ (Fux & Siegrist 2004). Electricity cost: €0.08 kWh⁻¹.