SEQUENCING BATCH REACTORS FOR NUTRIENT REMOVAL AT SMALL WASTEWATER TREATMENT PLANTS

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ABSTRACT

In order to optimize the sequencing batch reactor (SBR) process for nutrient removal at small wastewater treatment plants, a two year study was carried out at a treatment plant designed for 300 population equivalents. Different operating cycles, solids retention times (SRTs) and periods with co-precipitation were included in the test program. Based on the results, recommendations for achieving nitrification, denitrification and biological phosphorus removal were given. A suitable coagulant (and the optimum dosage) for co-precipitation was found as well.

KEYWORDS

Bio-P removal; co-precipitation; denitrification; municipal wastewater; nitrification; SBR.

INTRODUCTION

Since the late 1970s use of sequencing batch reactor (SBR) technology has gained widespread popularity for activated sludge treatment at small and medium sized municipal treatment plants (Irvine et al., 1979, 1987; Melcer et al., 1987). BIOVAC A/S has developed a prefabricated wastewater treatment plant using SBR technology and polyethylene reactors. Initially the BIOVAC SBR plants were successfully used to treat fairly concentrated wastewater from institutions and small businesses. However, with proper control systems SBR technology was also considered appropriate for handling the extremely variable and often dilute wastewater typical for small municipal wastewater treatment plants. A full-scale plant designed for 300 P.E. (population equivalents) was put in operation in 1990. This plant was built with an equalization and degritting tank and six SBR reactors. Not all the reactors are in use. The wastewater flow varies from about 50 to 200 m³/d, depending on weather conditions. Normal discharge criteria are ≤ 15 mg BOD/ℓ and ≤ 0.8 mg total P/l. There is no formal requirement for nitrogen removal.

An overall objective has been to keep the design of the SBR reactors simple and operator friendly. Hence, the reactors are not equipped with stirring devices since rags, hair, etc. in the influent may interfere with the operation of the stirrers. Pumps, valves and aerators for all the reactors are controlled by a programmable logic controller (PLC) which may change the preset cycle times for the different reactors depending on variations in the influent flow rate.
A test program was carried out at this full-scale plant, with a goal of optimizing the SBR process for phosphorus removal, nitrification and nitrogen removal. A matrix of different operating cycles was tested, including several runs with co-precipitation using pre-polymerized coagulants.

**EXPERIMENTAL DESIGN**

**Description of the treatment plant**

A simplified flow sheet of the treatment plant, with only one of the six SBR reactors, is shown in Fig. 1. Two reactors, later referred to as reactors 1 and 2 in Table 1, were used in the test program. Raw wastewater flowed to an equalization and degritting tank. Using this tank as a reservoir for pumping wastewater to the appropriate SBR reactor, fill time up to maximum volume was as low as 13 minutes. After completed treatment, the clarified effluent was drained from the reactor and a preset volume of waste activated sludge was drained to the unaerated sludge storage tank. Each SBR had a maximum water volume of 9.7 m³. A volume of 4.7 m³ was below the effluent drain and a settled sludge volume of 3.0 m³ was below the waste activated sludge drain. Aeration for aerobic operation was provided by a small blower and two rubber membrane disc diffusors at the bottom of each reactor. The reactors had no stirrers, hence mixing for anoxic operation was done by blowing air for three to six seconds every 15 minutes. For test-runs with co-precipitation, coagulants were dosed to the influent pipe during the fill period.

**Wastewater Characteristics**

Influent concentrations to the SBR reactors showed fairly large variations between the minimum and maximum values for each parameter. The mean influent concentrations for each test run can be found in Table 1. About 50% of the organic material was particulate (after pretreatment in the equalization tank) and a BOD₇/COD ratio of 0.35 indicates that the bulk of the organic material was slowly degradable. Particulate and soluble organic nitrogen accounted for 30 to 40% of the total nitrogen. The wastewater in the equalization tank normally had a fairly high oxygen concentration. All this is typical for fresh wastewater from areas with short and relatively steep sewers.

**Test Program**

Process phases, cycle times and average operating conditions for the 16 different test runs, are shown in Fig. 2 and Table 1. The operating cycles on top of Fig. 2 had only one fill period per cycle, followed by aerated reaction, settling and drain phases. For two of the cycles the drain phase was followed by an idling phase where the aeration was alternately on for 15 minutes and off for 15 minutes. The operating cycles at the bottom of Fig. 2 had multiple fill periods and anoxic (mixed) reaction phases in order to enhance denitrification. This multiple feed strategy has been described and simulated by Oles and Wilderer (1991.) In our tests, mixing was provided by a few seconds of aeration every 15 minutes.

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Fig. 1. Flow-sheet showing the equalization tank and one of the SBR reactors (with key data).
Sequencing batch reactors
for nutrient removal

Fig. 2. SBR process phases during one of operation shown for the different test runs.

Pre-polymerized, aluminium based coagulants were used for co-precipitation. Table 1 shows the coagulants and dosages used for test runs 12-16. All coagulants were in liquid form.

Monitoring and Analysis

Reactor pH, dissolved oxygen (DO), oxidation-reduction potential (ORP) and temperature were measured continually. Automatic samplers took 24 hr flow proportional influent and effluent samples in sampling points 1 and 3, respectively (see Fig. 1). Mixed liquor samples (sampling point 2) and waste activated sludge samples (sampling point 4) were taken manually.

All influent and effluent water samples were analyzed for total COD, filtered COD, NH₄-N, NO₂-N, NO₃-N, total P, PO₄-P, alkalinity and pH. Total BOD₇ was analyzed on one or two sets of samples for each test run. Total Kjeldahl nitrogen (TKN) was analyzed on all samples from test runs 7 to 11 and on one or two sets of samples from each of the other test runs. Suspended solids (SS) was only measured on a few samples. Glass fibre filters with an average pore size of 1 μm were used for filtration.

Reactor biomass and amount of waste activated sludge (sampling points 2 and 4) were measured as both MLSS and MLVSS. Sludge settleability was controlled daily by measuring sludge volume (SV) and sludge volume index (SVI).

RESULTS AND DISCUSSION

Average operating conditions and influent and effluent concentrations for each run are listed in Table 1. Aerobic solids retention time (SRT) ranged from 1.3 to 19 days. The hydraulic retention time (HRT) varied from 9.3 to 32 hours. Reactor MLSS ranged from 2270 to 3680 mg/l in test runs with biological treatment only, and from 2080 to 5210 mg/l in test runs with co-precipitation. Average wastewater temperatures in the reactors for each test run varied from 7.4 to 14.3°C, with a median value of 9.0°C.
### TABLE 1. Operating conditions and influent and effluent (in parenthesis) concentrations. Averages for each test run.

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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>12</td>
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<td>0.67</td>
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<td>(0.1)</td>
<td>(1.9)</td>
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<td>(1.2)</td>
<td>(1.5)</td>
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<td>(0.5)</td>
<td>(0.6)</td>
<td>(0.7)</td>
<td>(2.8)</td>
<td>(1.8)</td>
<td>(1.8)</td>
<td>(2.6)</td>
<td>(4.0)</td>
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* P=PAX 60P, E0=Entec 007, E1=Entec 118  ** g BOD₅/g MLVSS·d
Organic Matter Removal and Solids Separation

Excellent removal of organic matter was obtained. Average effluent concentration was 8 mg BOD₇/l for the test runs with biological treatment only, with minimum and maximum values of 3 and 13 mg BOD₇/l, respectively. For the test runs with co-precipitation the average effluent concentration was 6 mg BOD₇/l, with minimum and maximum values of 5 and 9 mg BOD₇/l. The effluent SS analysis indicated that co-precipitation led to slightly better solids separation, with median effluent concentrations of 8 mg SS/l for runs with co-precipitation and 14 mg SS/l for runs without co-precipitation. This difference may explain why somewhat lower BOD₇ concentrations were observed with co-precipitation than without.

Average SVI values reported from full-scale SBR plants have typically been between 120 and 160 ml/g (Irvine et al., 1987; Melcer et al., 1987). For the test runs with co-precipitation the SVI values ranged from 70 to 148 ml/g, with an average of 104 ml/g. The test runs with biological treatment only had SVI values from 85 to 188 ml/g, with an average of 116 ml/g. During settling dispersed sludge was never observed in the clear water phase, even though effluent SS concentrations around 30 mg/l were observed on a couple of occasions.

Nitrification

The nitrification process is influenced by factors such as aerobic SRT, temperature, pH, DO and the organic matter to nitrogen (C/N) ratio. At a given temperature, a minimum aerobic SRT is necessary for complete nitrification. Data obtained at different temperatures may be used in the same graph by introducing a temperature compensated aerobic SRT. A temperature coefficient of $\theta = 1.103$ (EPA, 1975) has been used to calculate the aerobic SRTs at 10°C with the equation $SRT_{10} = SRT_T \cdot 1.103(T-10)$, where $T$ is the actual temperature in °C. Fig. 3 shows effluent NH₄-N concentrations versus the temperature compensated (10°C) aerobic SRT. In order to guarantee an effluent NH₄-N concentration below 2 mg/l at 10°C, a minimum aerobic SRT of 12-13 days was found. This is in agreement with the frequently used value of 12 days aerobic SRT for full nitrification in activated sludge systems at 10°C, given by Christensen and Harremoës (1978). The scatter at low aerobic SRTs in Fig. 3 is due to the highly variable influent TKN and NH₄-N concentrations.

Because of simultaneous ammonification and nitrification during aerated phases and denitrification during settling, the true nitrification rates can only be found by using data from intensive studies with frequent grab sampling throughout the operating cycle. Fig. 4 shows specific nitrification rates versus aerobic SRT, where both the nitrification rates and the aerobic SRT have been temperature compensated to 10°C. The maximum nitrification rate at 10°C was found to be 1.8 - 1.9 mg NO₃-N/g MLVSS•h. This is significantly higher than the expected nitrification rate of 1.0 mg NH₄-N/g MLVSS•h given by Christensen and Harremoës (1978) for activated sludge systems with combined carbon removal and nitrification. It is, however, only 10% higher than the maximum nitrification rates measured at large activated sludge plants in Sweden with a similar influent C/N-ratio (SNV, 1991).

Fig. 4 indicates that the biomass sustained a fairly high specific nitrification rate, until the aerobic SRT was reduced to a critical level where the nitrifying bacteria were washed out of the system. This critical aerobic SRT at 10°C seemed to be in the range of 4 to 6 days, which agrees well with reported maximum specific growth rates for nitrifying bacteria in activated sludge (Antoniou et al., 1990). At aerobic SRTs below 12 to 13 days, but above the critical value for wash out of nitrifiers, complete nitrification was not obtained (see Fig. 3) due to TKN loads higher than the maximum specific nitrification rates.

Low alkalinity and low pH was sometimes a problem. Due to batch operation, however, nitrification was normally inhibited by low pH only at the end of an operating cycle, after the available alkalinity had been depleted through the previous ammonium reduction.
Denitrification

The denitrification rate is dependent on the temperature, the NOX-N concentration and the type and concentration of the carbon source. Specific denitrification rates, based on data from intensive studies during runs with anoxic operation phases, are given in Table 2. In test run 7 denitrification after the first fill was obviously limited by low NOX-N concentration. The maximum denitrification rates of 0.4-0.5 mg NOX-N/g MLVSS•h after the second and third fill were probably limited partly by the low NOX-N concentrations and partly by inadequate mixing.

In test run 9 the mixing intensity was increased from 3 to 5 seconds of aeration every 15 minutes. The mean specific denitrification rates were limited by lack of biodegradable soluble COD. However, the maximum denitrification rates were as high as 1.36 and 1.15 mg NOX-N/g MLVSS•h after the second and third fill, respectively. For test run 10 the mixing intensity was increased to 6 seconds of aeration every 15 minutes. After the first fill the DO concentration was low and both the mean and the maximum denitrification rates were 1.15 mg NOX-N/g MLVSS•h. After the second and third fill the mean specific denitrification rates were limited by high DO concentrations during the initial 10 to 30 minutes of the anoxic phases and low biodegradable soluble COD at the end of the anoxic phases. Maximum denitrification rates were approximately 1.2 mg NOX-N/g MLVSS•h.
Sequencing batch reactors for nutrient removal

TABLE 2. Specific Denitrification Rates at Stated Operating Conditions. Temperatures of 8.9-9.8°C

<table>
<thead>
<tr>
<th>Test run</th>
<th>Fill no.</th>
<th>% of total fill</th>
<th>Mixing, sec.</th>
<th>Eff. NO₃-N, mg/l</th>
<th>BSCOD, g BOD₅/g TN</th>
<th>**C/N, Mean DN rate, mg NO₃-N/g MLVSS·h</th>
<th>Maximum DN rate, mg NO₃-N/g MLVSS·h</th>
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<tr>
<td>7</td>
<td>1</td>
<td>50</td>
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* Biodegradable soluble COD at end of anoxic phase, measured as filtered COD at end of anoxic phase minus filtered COD at end of the following aerobic phase.
** Mean value for all fill periods in one cycle.

The aeration mixing showed no effect on the DO level in the reactors. At temperatures of 9 to 10°C normal specific denitrification rates of 0.3 to 1.2 mg NO₃-N/g MLVSS·h, depending on wastewater quality, have been reported (Jansen, 1991). Both the mean and the maximum denitrification rates obtained in test runs 9 and 10 compare favourably to these normal rates. Hence, aeration mixing for 5 to 6 seconds every 15 minutes was a good substitute for mechanical stirrers during anoxic operation.

Removal of total nitrogen

Total nitrogen (TN) is removed partly by denitrification and partly by settling of particulate nitrogen. Denitrification may take place during idling, settling and fill phases, in addition to the phases with anoxic mixing. Fig. 5 shows TN removal versus TKN reduction, based on the averages from the 16 test runs. Figures above and below each data point indicate aerated fraction and influent C/N-ratio (as g BOD₅/g TN), respectively. Approximately 35% TKN reduction was achieved by assimilation and separation of particulate nitrogen, thus a minimum of 35% TN removal was always achieved. Higher TN removal required some degree of nitrification and denitrification. For the test runs with co-precipitation, maximum TKN reduction was about 60% and less than 50% TN was removed. For test runs with biological treatment only and high TKN reduction, 60-65% TN removal was achieved with C/N-ratios of 2.5-3.1 g BOD₅/g TN and aerated fractions of 0.46-0.57. The data showed that at a given TKN reduction, a high aerated fraction had a detrimental effect and a high C/N-ratio had a positive effect on the TN removal.

Fig. 5. Removal of total nitrogen versus TKN reduction, based on averages from the 16 test runs.
Introducing anoxic phases had no apparent effect. However, the three data points to the far right in Fig. 5 had significantly longer aerobic SRTs and lower temperatures than the data point to their left. The long SRT and low temperature led to reduced denitrification during settling, which means that significantly lower TN removal would have been achieved without anoxic phases. For runs with short SRT and aerated fractions below 0.6, almost complete denitrification of the settled sludge volume was observed.

For most of the test runs the influent C/N-ratios were significantly lower than the C/N-ratio of 4-6 g BOD/g TN normally considered necessary for a high degree of TN removal (Harremoes et al., 1985). The results from the denitrification tests confirmed that denitrification was limited by lack of soluble carbon in several test runs. In order to achieve more than 60-65% TN removal, it will be necessary to introduce longer anoxic phases with utilization of endogenous carbon for denitrification.

**Phosphorus Removal**

**Co-precipitation.** The dosages and type of coagulants used for co-precipitation have previously been shown in Table 1. Average removal efficiencies were 93% for total P and 96% for PO₄-P. Effluent total P and PO₄-P concentrations versus the Al/P molar ratio (based on influent total P) are shown in Fig. 6. The dotted lines indicate the maximum effluent total P concentration observed at a given Al/P molar ratio for each coagulant. In order to guarantee an effluent concentration below 0.5 mg total P/l critical Al/P molar ratios of about 1.4 mol Al/mol P for PAX 60P, 1.7 mol Al/mol P for Entec 118 and 2.7 mol Al/mol P for Entec 007 were found. For the Entec products these molar ratios were based on very few observations and should be used with caution. The results showed, however, that PAX 60P was a good coagulant based on the amount of Al used.

A survey of 43 small Norwegian activated sludge plants with co-precipitation showed a median effluent concentration of 1.2 mg total P/l (Rusten and Paulsrud, 1990). In comparison the BIOVAC SBR plant with co-precipitation performed very well, with a median effluent concentration of 0.4 mg total P/l.

**Biological phosphorus removal.** Excellent biological phosphorus removal was observed during test runs 7 and 8 and during the running in period for test run 11. Only partial nitrification was obtained in runs 7 and 8 and all the NO₃-N in the settled sludge volume was denitrified prior to the first fill and the first anoxic phase. Thus the soluble, easily biodegradable organic matter in the raw water from the first fill was available for the polyphosphate storing bacteria. The typical bio-P removal features, with release of PO₄-P during the first anoxic phase and uptake of PO₄-P during the following aerobic phase, was observed. The ORP was typically 160 mV during aeration, dropping to 30 mV during settling and -110 mV during the first anoxic phase. Normal DO level during anoxic phases was 0.1 mg/l. Effluent PO₄-P and total P concentrations are shown in Fig. 7. Average removal efficiencies, including all the data points in Fig. 7, were 88% for total P and 91% for PO₄-P. Increased levels of total P were observed on two accounts, due to separation problems and effluent concentrations of about 20 mg SS/l and 30 mg SS/l, respectively. Excluding these two data points, the average total P removal was 91%.

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**Fig. 6.** Effluent total P AND PO₄-P versus the Al/P molar ratio for all the samples with co-precipitation.
Sequencing batch reactors for nutrient removal

In order to improve nitrification, the cycle time was increased from 12 to 16 hrs after test runs 7 and 8 were finished. Preparing for test run 11, the effluent NO\textsubscript{X}-N gradually increased. When the effluent concentration approached 10 mg NO\textsubscript{X}-N/l, denitrification of the settled sludge volume was incomplete and the bio-P removal was gradually lost. The start of this increase in effluent PO\textsubscript{4}-P concentration can be seen from the last data point in Fig. 7. No bio-P removal was observed in test runs 10 and 11. Normal DO levels during anoxic operation were 0.1-0.2 mg/l. However, NO\textsubscript{X}-N concentrations were always high and the ORP was never below -40 mV.

Altogether, the results indicated that bio-P removal could only be achieved if the settled sludge was completely denitrified prior to the first fill and the first anoxic phase. At high SRTs and high effluent NO\textsubscript{X}-N concentrations this may possibly be done by introducing an anoxic idling period between the decant and first fill phases.

**SUMMARY AND CONCLUSIONS**

*The small SBR plant performed well throughout the study. Average effluent concentrations of 6 mg BOD\textsubscript{5}/l and 8 mg BOD\textsubscript{5}/l, respectively, were obtained for test runs with and without co-precipitation.*

*At 10°C complete nitrification was achieved at aerobic SRTs above 12-13 days, the maximum specific nitrification rate was 1.8-1.9 mg NO\textsubscript{X}-N/g MLVSS\textsubscript{h} and the nitrifiers were washed out of the reactors at aerobic SRTs below 4-6 days.*

*Maximum specific denitrification rates of 1.2-1.3 mg NO\textsubscript{X}-N/g MLVSS\textsubscript{h} were measured at 9-10°C. Aeration mixing for 5-6 seconds every 15 minutes was a good substitute for mechanical stirrers during anoxic operation.*

*Total nitrogen removal of 60-65% was achieved with influent C/N-ratios of 2.5-3.1 g BOD\textsubscript{5}/g TN and aerated fractions of 0.46-0.57.*

*During the tests with co-precipitation a critical dosage of 1.4 mol Al/mol P was found in order to guarantee effluent concentrations below 0.5 mg total P/l, using the coagulant PAX 60P.*

*For test runs where the operating cycle started with an anoxic phase, biological P-removal was observed if the settled sludge was completely denitrified prior to the first fill. Median effluent concentrations during the period with biological P-removal were 0.56 mg total P/l and 0.18 mg PO\textsubscript{4}-P/l.*

**REFERENCES**


