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NITRIFICATION MONITORING IN ACTIVATED SLUDGE BY OXYGEN UPTAKE RATE (OUR) MEASUREMENTS

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Abstract—A simple measuring system was developed that yields information about the presence of NH_4^+ and NO_2^- nitrogen in mixed liquor samples. In addition, it allows monitoring of the rate of both NH_4^+ and NO_2^- oxidation simultaneously with the carbon substrate oxidation using OUR measurements. The method is based on the subsequent addition of $NaClO_3$ and allylthiourea, selective inhibitors of *Nitrobacter* and *Nitrosomonas* respectively, to the mixed liquor sample in a closed batch respirometer. The presented method is valuable for detailed monitoring of the nitrification process in a reactor: it is simple, inexpensive, robust and generally applicable for nitrifying reactor systems. The measurement of NH_4^+ and NO_2^- oxidation rates enables the operator to detect the presence of NH_4^+ and NO_2^- species. This allows action to be taken to improve the performance of the system. The method is validated on a SBR. It is indicated that optimal SBR phase scheduling can be based on such OUR measurements. Copyright © 1996 Published by Elsevier Science Ltd.

Key words—biological nutrient removal, nitrification, activity measurements, allylthiourea, sodium chlorate, sequencing batch reactor, control, inhibition, oxygen uptake rate

INTRODUCTION

Removal of nitrogen and phosphorus has become an essential part of activated sludge processes as a result of the concern for eutrophication of the effluent receiving waters. Anoxic, anaerobic and aerobic conditions are essential to accomplish biological nutrient removal.

For nitrogen removal, a sequence of nitrification and denitrification is necessary. Nitrification is performed by two populations: the *Nitrosomonas* group oxidizes NH_4^+-N to NO_2^--N; the *Nitrobacter* group subsequently converts NO_2^--N to NO_3^--N.

It is difficult to monitor and adjust nitrification in a plant in operation. The decrease of the substrate (NH_4^+-N) and increase of the end-product (NO_3^--N) gives information but does not reflect the actual activity of the nitrifiers. There would be more control possibilities when changes in activity of the nitrifiers could be observed. Influents with strongly varying concentrations of COD and nutrients can cause two types of non-optimal behaviour of the treatment plant. Overloading of the activated sludge will endanger complete nitrification; the presence of NH_4^+-N in the effluent will be the consequence. Underloading of the activated sludge will give rise to a wastage of aeration energy.

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It could be useful to have a biological method capable to detect the presence of NO_2^--N in mixed liquor samples. Nitrite is a toxic nitrification intermediate whose formation has already been studied intensively (Balmelle *et al.*, 1992; Yang and Alleman, 1992; Abeling and Seyfried, 1993; Baten *et al.*, 1993).

The nitrification part of the biological nutrient removal process is generally recognized as the most vulnerable activated sludge process, depending on many factors which are often interconnected. To monitor the activity of the nitrifying populations present in activated sludge, Nowak and Svardal (1993) estimated the kinetic parameters of nitrifying biomass under the inhibiting conditions obtained by the presence of particular wastewaters. This was carried out by measuring the OUR of the nitrifying biomass at different NH_4^+-N concentrations. Allylthiourea (ATU), a selective inhibitor of the *Nitrosomonas* group, was used to inhibit nitrification. Vanrolleghem and Verstraete (1993) characterized mixed heterotrophic and nitrifying activated sludge populations using respirometry. They could distinguish the OUR for nitrification and carbon oxidation by choosing the appropriate composition of the calibration substrate used in their on-line RODTOX respirographic biosensor.

Selective inhibitors of NH_4^+ and NO_2^- oxidation have been described to determine the nitrifying activity of a sludge. In this paper, the nitrifying activity is defined as the amount of NH_4^+ or NO_2^-

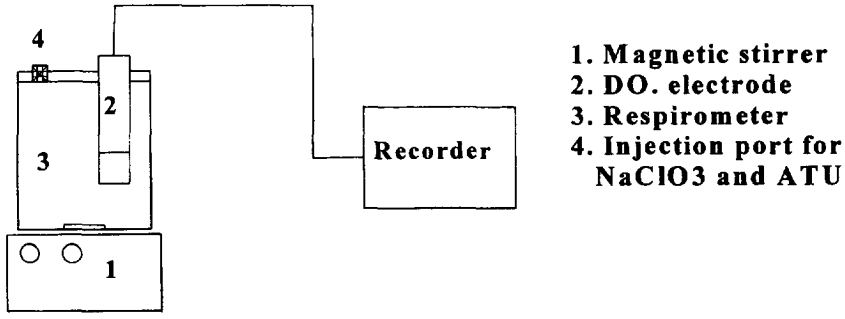

Fig. 1. Fed batch respirometer used for recording oxygen uptake rate profiles.

oxidized per liter sludge per hour and is expressed as the corresponding oxygen consumption rate in mg O_2/l·h. The inhibitors commonly used are $NaClO_3$ and ATU (Völsch *et al.*, 1990). $NaClO_3$ is an inhibitor of NO_2^- oxidation by *Nitrobacter* at a concentration of 20 mM (Belser and Mays, 1980; Hynes and Knowles, 1983; Völsch *et al.*, 1990). $NaClO_3$ exerts no immediate negative effects on NH_4^+-N oxidation by *Nitrosomonas* bacteria. Its inhibitory effect on *Nitrosomonas* becomes detectable only after approx. 30 min, due to the slow conversion of $NaClO_3$ to $NaClO_2$, which inhibits both *Nitrobacter* and *Nitrosomonas* (Hynes and Knowles, 1983). ATU is a selective inhibitor of NH_4^+ oxidation by *Nitrosomonas* at a concentration of 5 mg/l (Wood *et al.*, 1981; Völsch *et al.*, 1990). Völsch *et al.* (1990) proposed a method for the determination of NH_4^+ or NO_2^- degradation rates. They used the NO_2^--N production rate of a mixed liquor sample in the presence of $NaClO_3$ (*Nitrobacter* inhibited) as a measurement for the NH_4^+-N degradation rate. The NO_2^--N degradation rate in the presence of ATU (*Nitrosomonas* inhibited) was used as a measure for the *Nitrobacter* activity. The completion of one test took about 30 min.

The purpose of this work is to develop a rapid, simple and robust method for the determination of NH_4^+-N and NO_2^--N oxidation rates by measuring the OUR of mixed liquor samples before and after addition of selective nitrification inhibitors in a specific experimental setup. It was verified if the measured NH_4^+-N and NO_2^--N oxidation rates corresponded with the NH_4^+-N and NO_2^--N concentrations in the mixed liquor. Validation of the method was done on a SBR.

PRINCIPLE OF THE METHOD

A conventional fed batch respirometer (Fig. 1) with a small, completely closed reactor vessel (volume = 100 ml) was used for the measurements. The respirometer contained an oxygen electrode connected to a recorder. Mixed liquor samples were taken from the SBR, saturated with oxygen by shaking the sample and transferred to the vessel. This vessel was carefully closed, with no air bubbles

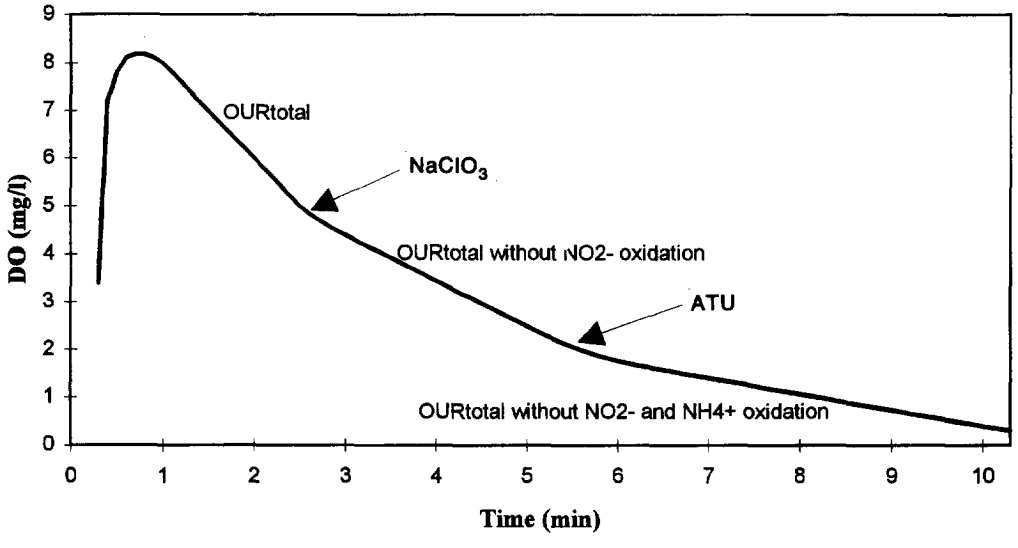

Fig. 2. Schematic representation of a typical oxygen uptake profile recorded with the developed nitrification activity determination method.

remaining in it. Samples were mixed during measurements by means of a magnetic stirrer at 150 r.p.m. Temperature and pH in the respirometer were the same as in the SBR.

The activity measurements result in oxygen uptake profiles as illustrated in Fig. 2. The operating procedure is as follows. First, the total OUR is determined. After the DO concentration has decreased with about 3 mg/l, $NaClO_3$ is added to the mixed liquor sample (final concentration is 20 mM $NaClO_3$ or 2.13 g/l) and the OUR is determined. The difference between the total OUR and the OUR measured in the presence of $NaClO_3$ is considered as the oxygen uptake due to the NO_2^--N oxidation (Fig. 3). Finally, after the DO has decreased with another 2 mg/l, ATU is added to the mixed liquor sample (final concentration is 5 mg/l) and the remaining OUR is measured. The difference between the OUR with $NaClO_3$ and both inhibitors, $NaClO_3$ and ATU, represents the oxygen uptake due to NH_4^+-N oxidation. The OUR measured in presence of both inhibitors reflects the oxygen consumption of the heterotrophs. The activity of the heterotrophic organisms consists of two components: oxygen consumption for substrate oxidation and endogenous respiration. It is not possible with this method to distinguish the heterotrophic substrate oxidation rate from the endogenous respiration rate. The selective inhibitors are freshly prepared stock solutions of ATU (125 mg/l) and $NaClO_3$ (0.5 M). Each time, the OUR is obtained by calculating the slope of the linear parts of the recorded DO profiles as illustrated in Fig. 2. The linearity of the curves was always checked. A linear curve indicates 0 order kinetics.

The repeatability of the method was verified in a separate experiment. A vessel containing 5 l of activated sludge was aerated overnight, until all COD and NH_4^+-N were converted (endogenous respiration). The NH_4^+-N oxidation rate was determined 5 times immediately after adding 1 mg NH_4^+-N to 5 different 100 ml sludge samples taken from the 5 l of sludge. An average activity of 18.5 ± 1.6 mg O_2/l·h has been calculated (initial NH_4^+-N concentration in mixed liquor = 10 mg/l). Hence, the repeatability was good. Subsequently, the NO_2^--N oxidation rate was determined 5 times after adding NO_2^--N to 100 ml sludge samples (initial concentration = 10 mg NO_2^--N/l mixed liquor). An average NO_2^--N oxidation rate of 2.7 ± 0.45 mg O_2/l·h was obtained. The repeatability of the NO_2^--N oxidation rate determination is less, probably because the activity of *Nitrobacter* bacteria was rather low.

MATERIALS AND METHODS

To evaluate the new method, experiments were performed on a 430 l pilot scale sequencing batch reactor (SBR) for nutrient removal. The reactor receives sewage from the city of Gent. The sewage mainly consists of domestic wastewater but at regular intervals also contains inputs (up to 20% of the COD load) of textile industry wastewater. The pilot plant was operated in a mode ensuring both organic carbon and nutrient (N and P) removal (Demuynck *et al.*, 1994). Aeration (C1), stirring devices (R1), dosing pumps (DPA and DPB) and valves were controlled by a PC with input/output card (Fig. 4).

Presettling of the raw wastewater was realised by means of a parallel plate separator (PPS). The presettled influent is then stored in a flow-through buffer tank, where it is gently stirred to avoid further settling of suspended matter. The hydraulic retention time in the buffer tank was about 6 min, due to the high flow rate of presettled wastewater coming from the parallel plate separator (50 l/min). At the beginning of a cycle, 200 l influent from the buffertank is added to the 230 l of mixed liquor remaining after decantation. The SBR cycles were performed according to the time schedule given in Table 1 to achieve nitrogen, phosphorus and BOD removal. Every day, 4 cycles of 6 h were performed.

During aerobic phase 1 (Table 1), mixed liquor samples were taken at regular time intervals from the SBR. No measurements were performed during the other periods of

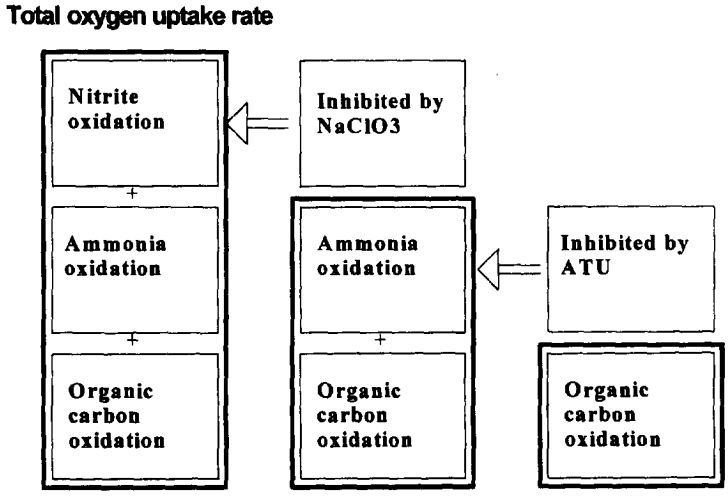

Fig. 3. Schematic representation of the action of $NaClO_3$ and ATU on the respiratory activity of the activated sludge.

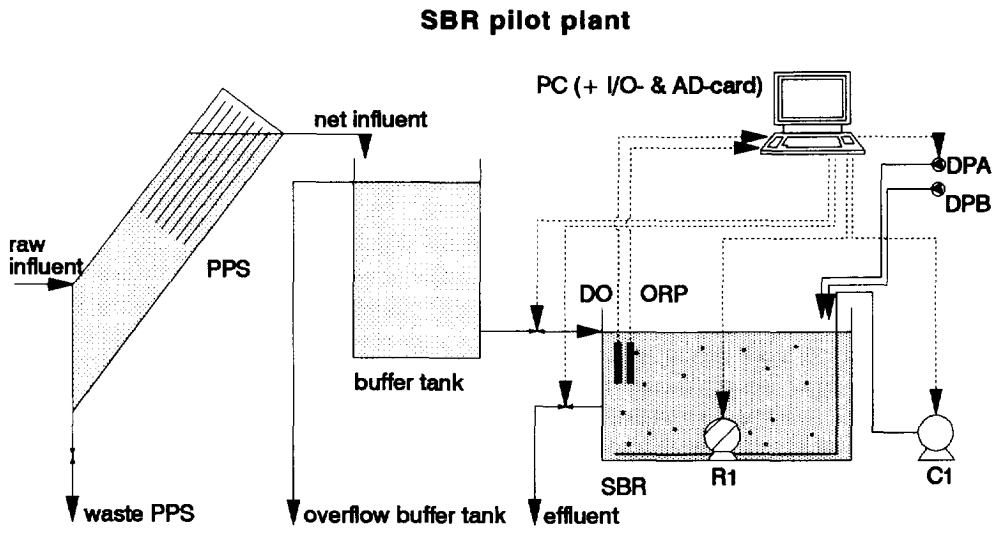

Fig. 4. Schematic overview of the SBR pilot-plant. PPS = parallel plate separator (V = 160 l); buffer tank (V = 300 l); SBR = sequencing batch reactor (V = 430 l); DO = DO-electrode; ORP = oxidation-reduction potential electrode; DPA, DPB = dosing pumps and valves; R1 = stirring device; C1 = aeration pump (Q_{max} = 22 m^3/h).

the SBR cycle. To avoid errors due to sampling, samples were always taken at the same well mixed place in the SBR. Each mixed liquor sample was divided into 3 parts (Fig. 5). A first part was used for the measurement of NH_4^+-N and NO_2^--N oxidation rates, as described above. A second part of the sample was filtered and then immediately used for the determination of NO_2^--N. Nitrite was determined colorimetrically according to the method of Montgomery and Dymock (1961). Ammonium and NO_2^--N oxidation rates and NO_2^--N concentration were measured immediately after sampling from the SBR. Finally, a third part of the mixed liquor sample was stored at 4°C after filtration and acidification with a few drops of concentrated HCl. The acidified samples were afterwards used in the lab for COD, NH_4^+-N and NO_3^--N determination. COD and nitrogen compounds concentrations were analysed according to

Table 1. SBR reaction sequence for nutrient removal (Demuynck *et al.*, 1994)

Phase	Purpose	Length (min)
Anaerobic + filling	P release	60
Aerobic 1	P uptake, nitrification, COD removal	150
Anoxic	Denitrification	60
Aerobic 2	Excess COD removal, N_2 stripping	30
Settling	Sedimentation	45
Decanting	Decantation	15
	Total cycle time	360

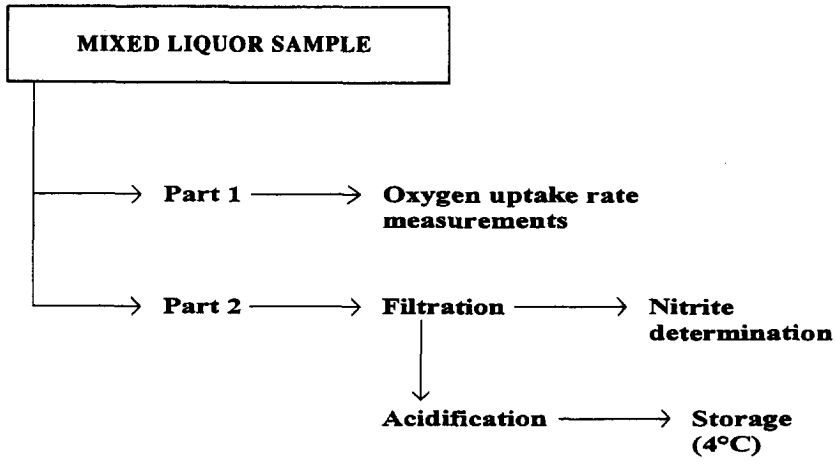

Fig. 5. Sampling procedure for the SBR. Each time, a mixed liquor sample was divided into 3 parts. The first part was used for OUR measurements, the second part for NO_2^--N determination and the third part for lab analyses.

Standard Methods (APHA, 1985). Short term BOD was determined with the RODTOX activated sludge biosensor (Vanrolleghem *et al.*, 1994).

Three test runs were performed with the new method. A situation of normal loading was compared to situations with underloaded and overloaded sludge.

RESULTS

An example of the variable BOD concentration in the influent of the SBR pilot plant is shown in Fig. 6(A). This figure, representing BOD concentrations measured on the presettled wastewater in the buffer tank during a one week period, clearly shows how the influent BOD concentration fluctuates from hour to hour, resulting in strongly varying loading conditions for the treatment plant. Figure 6(B) illustrates the evolution of NH_4^+-N and TKN concentrations in the influent during a representative period of approximately one month. With sufficient plant flexibility, it can be expected that process control could be useful to cope with the variable influent composition.

The experiments to validate the method were performed under three totally different nitrogen loading conditions (Table 2). Different loading conditions were caused by the variable influent composition, as illustrated before (Fig. 6).

Figure 7 represents the evolution of the COD and the nitrogen species [Fig. 7(A)] and different oxidation rates [Fig. 7(B)] for aerobic phase 1 (see Table 1) of a SBR cycle. The activated sludge had a normal loading and the aeration time was sufficient to obtain complete nitrification. After 60 min, COD removal was completed and the residual COD level remained constant. This is illustrated by the finding that the heterotrophic OUR stabilized from this moment at a low level corresponding with endogenous respiration [Fig. 7(B)]. After 80 min, NH_4^+-N was almost completely eliminated from the mixed liquor and the NH_4^+-N oxidation rate became zero. After 100 min, nitrification was completed: all NO_2^--N had been converted to NO_3^--N. At that moment the NO_3^--N concentration reached a maximum. With 50 min remaining in the aerobic phase I, this shows that the SBR could handle a higher nitrogen loading under the given circumstances. In other words, aeration could already be stopped after 80 min and the denitrification phase could be initiated.

A limited NO_2^- build-up was observed. When NO_2^--N was at its highest level (1.55 mg NO_2^--N/l), the NO_2^--N oxidation rate reached a maximum (24.5 mg O_2/l·h) [Fig. 7(B)]. Subsequently the activity of NO_2^- oxidizing bacteria decreased with decreasing

Table 2. Approximate nitrogen loading conditions used in the 3 experiments performed to evaluate the nitrification activity measurement device

Loading conditions	mg Kj-N/l·cycle	mg Kj-N/l·d
(1) Normal loading	15	60
(2) Underloaded sludge	5	20
(3) Overloaded sludge	25	100

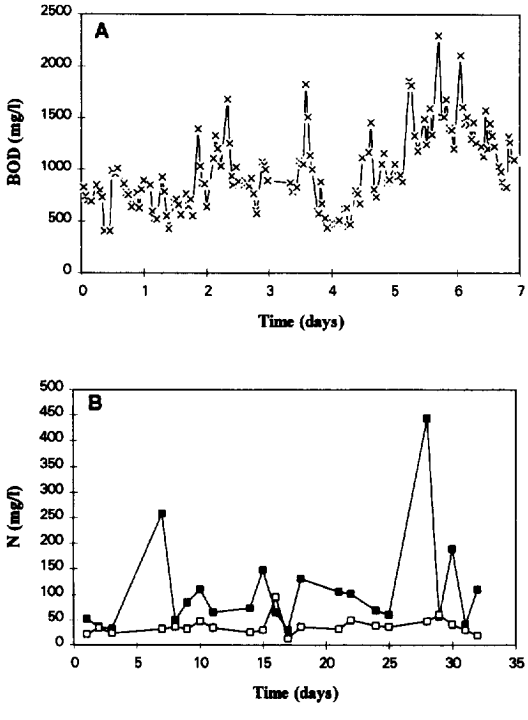

Fig. 6. Variable influent composition of the wastewater entering the wastewater treatment plant. (A) Typical BOD variation in the influent of the SBR pilot plant during a one-week period. (B) Daily variation of influent TKN (■) and NH_4^+-N (□).

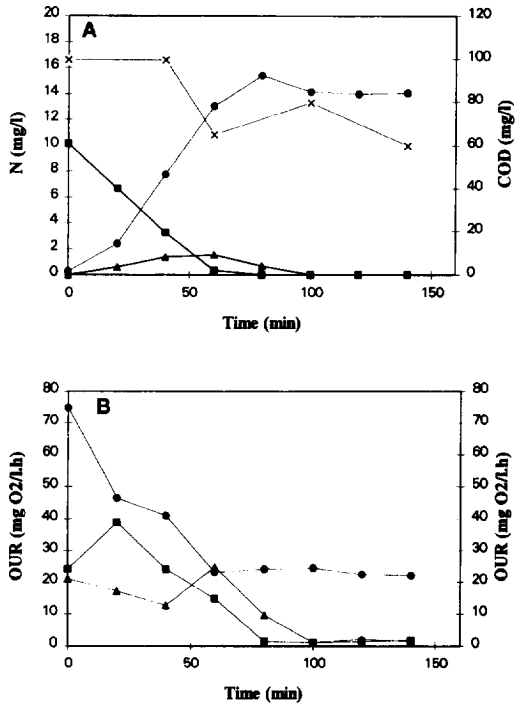

Fig. 7. Typical aerobic 1 phase in a SBR cycle with normal nitrogen loading. (A) COD (×), NH_4^+ (■), NO_2^- (▲) and NO_3^--N (●) concentration. (B) NH_4^+ (■), NO_2^- (▲) and heterotrophic substrate oxidation rate (●).

NO_2^--N concentrations to become nil when the substrate for *Nitrobacter* bacteria was exhausted. An almost identical relationship was observed between the NH_4^+-N concentration and the NH_4^+-N oxidation rate. Only at the very beginning of the aerobic phase, the NH_4^+-N oxidation rate was low with regard to the NH_4^+-N concentration in the reactor.

A similar relationship between changes of the nitrogen species and NH_4^+ and NO_2^--N oxidation rates was found for underloaded sludge. Underloaded sludge needed about 60 min to complete both NH_4^+-N and NO_2^--N oxidation (Fig. 8). Under this loading condition, the maximum NO_2^--N concentration (0.70 mg NO_2^--N/l) and the maximum NO_2^--N oxidation rate (21 mg O_2/l·h) coincided after 20 min of aeration. After 1 h, neither the COD nor the heterotrophic OUR were subject to further changes. The oxidation rate measurements showed that for this cycle substrate oxidation processes were fully completed after approximately 60 min of aeration.

A different picture was observed in case of sludge overloading. The presetted time of 150 min for nitrification was found too short: only the NH_4^+-N oxidation was nearly finished (Fig. 9). After an aeration period of 150 min, there was still 1.0 mg NH_4^+-N/l present in the mixed liquor. As the NH_4^+-N concentration decreased, the NH_4^+-N oxidation rate first increased and then, after 120 min, when NH_4^+-N started to become rate limiting, the NH_4^+-N oxidation rate decreased. Yet, it did not drop to very low levels, suggesting the ongoing metabolic activity of the *Nitrosomonas* population. This corresponds with the low amount of NH_4^+-N that was still remaining in the reactor liquid. The fact that none of the 3 oxidation rates (for NH_4^+-N, NO_2^--N and heterotrophic substrate oxidation respectively) reached a low level at the end of the cycle reflected the incompleteness of the oxidation processes. For this cycle, oxidation rate measurements clearly showed that 150 min aeration was insufficient to complete NH_4^+-N and COD oxidation. Also, based on the NO_2^--N oxidation rate, it could be concluded that the mixed liquor still contained NO_2^--N at the end of the aerobic cycle.

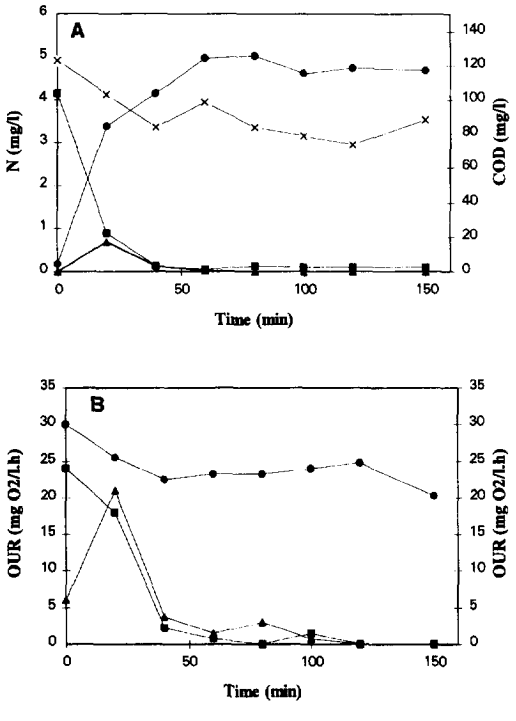

Fig. 8. Aeration step in a SBR cycle with underloaded sludge. (A) COD (×), NH_4^+ (■), NO_2^- (▲) and NO_3^--N (●) concentration. (B) NH_4^+ (■), NO_2^- (▲) and heterotrophic substrate oxidation rate (●).

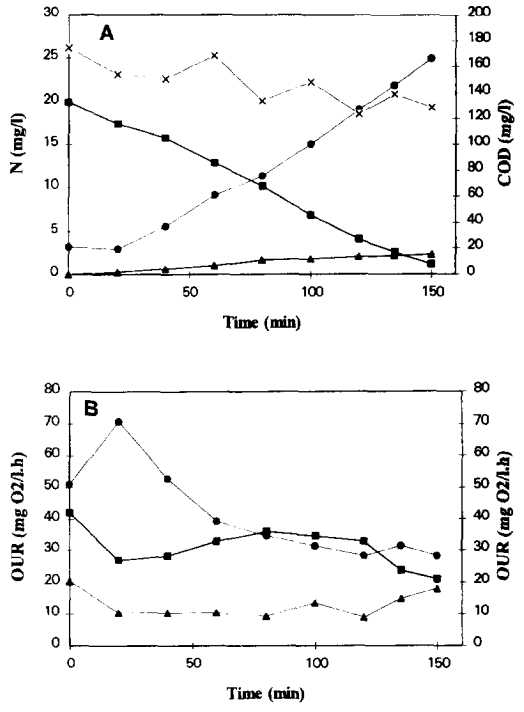

Fig. 9. Aeration step in a SBR cycle with overloaded sludge. (A) COD (×), NH_4^+ (■), NO_2^- (▲) and NO_3^--N (●) concentration. (B) NH_4^+ (■), NO_2^- (▲) and heterotrophic substrate oxidation rate (●).

Ammonium oxidation rates determined under 3 different loading conditions were plotted against NH_4^+-N concentrations. The oxidation rates at the beginning of the aerobic phase (time = 0) were not used for these plots, because these values are endowed with large standard errors. Aerobic conditions are not always completely fulfilled at that moment (short transition phase between anaerobic and aerobic phases), which could result in low oxidation rates due to the fact that oxygen is a limiting substrate for the nitrifying bacteria.

Figure 10 shows that a relationship was found between NH_4^+-N oxidation rate and NH_4^+-N concentration. According to this figure, the NH_4^+-N oxidation rate is inhibited by its own substrate. The

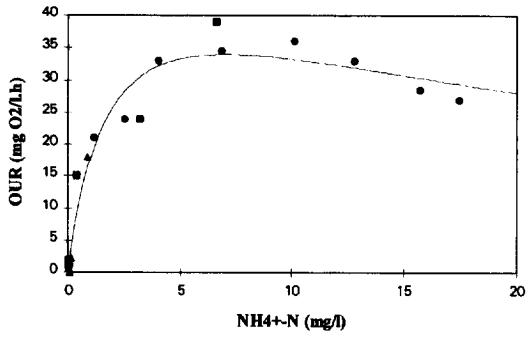

Fig. 10. NH_4^+ oxidation rate plotted as a function of NH_4^+-N concentration. Experimental datapoints (■ = data for normal loaded sludge; ▲ = data for underloaded sludge; ● = data for overloaded sludge) are compared with the curve (full line) representing the Haldane competitive inhibition kinetics model with $r_{max} = 52.24$ mg $O_2/l \cdot h$, $K_M = 1.9$ mg NH_4^+-N/l and $K_I = 26.27$ mg NH_4^+-N/l.

experimental datapoints were fitted by the Haldane competitive substrate inhibition kinetics model (Han and Levenspiel, 1988). This model can be described as

$$r = r_{max} \frac{C_s}{K_M + C_s + \frac{C_s^2}{K_I}}.$$

The parameters for the curve that fitted the datapoints were: $K_M = 1.9$ mg NH_4^+-N/l, $r_{max} = 52.24$ mg $O_2/l \cdot h$ and $K_I = 26.27$ mg NH_4^+-N/l. No trend could be deduced for the NO_2^--N oxidation rates plotted as a function of NO_2^--N concentration.

DISCUSSION

Ammonium and nitrite oxidation rates could be measured with a batch respirometer using selective inhibitors to nitrifying sludge samples. The method is fast (one measuring cycle takes approx. 10 min) and its repeatability is good, which makes it a powerful instrument to monitor nitrification in activated sludge tanks. Respirometry without use of inhibitors measures the oxygen consumption for C oxidation and nitrification as one signal. ATU was already used to distinguish between nitrification and C oxidation (Stensel *et al.*, 1976; Kroiss *et al.*, 1992; Nowak and Svardal, 1993). With this paper, it is shown that dosing both $NaClO_3$ and ATU gives extra value to respirometric methods. When operated this way, respirometry can give a detailed view of 3 different oxidation processes: C oxidation, NH_4^+ oxidation and NO_2^- oxidation. The use of two selective inhibitors allows to determine NH_4^+-N and NO_2^--N oxidation rates with one single experiment. Völsch *et al.* (1990) also used $NaClO_3$ and ATU as selective nitrification inhibitors, but they needed 2 experiments to get the same information as in the proposed method. One experiment took about 30 min while the method proposed in this paper takes about 10 min.

Vanrolleghem and Verstraete (1993) did not use inhibitors because the sludge in the respirometer used for their experiments is used for several consecutive substrate injections, when operated in the on-line mode. However, a method was proposed to still distinguish between OUR for nitrification and carbon oxidation. It is based on an appropriate design of the composition of the calibration substrate used in the on-line RODTOX respirometric biosensor. Our method maybe yields less information but is inexpensive and can be carried out more easily than the procedure proposed by Vanrolleghem and Verstraete (1993). Moreover, the proposed method evaluates the current state of the sludge and the nitrogen species in the monitored system, while the method of Vanrolleghem and Verstraete (1993) evaluates the heterotrophic and nitrifying activity of the sludge in the RODTOX. Nowak and Svardal (1993) aerated sludge samples until NO_2^--N was completely oxidized, before they used ATU as a nitrification inhibitor to measure the total autotrophic nitrification activity. Hence, no differentiation could be made.

During the measurements with the proposed method, a limited NO_2^- build-up takes place after $NaClO_3$ addition, because *Nitrobacter* bacteria are at that moment inhibited. For a measured NH_4^+-N oxidation rate of 20 mg $O_2/l \cdot h$, this will result in a NO_2^- build-up of about 0.6 mg NO_2^--N/l assuming that $NaClO_3$ addition took place 6 min before the end of the measurement. Such NO_2^--N levels do not inhibit nitrification according to Anthonisen *et al.* (1976).

To optimize operating conditions, OUR measurements for the determination of NH_4^+-N and NO_2^--N oxidation rates are proposed. When for instance being applicated on a nitrifying activated sludge system, the method should allow to detect the presence of NO_2^--N in the mixed liquor. These data could be used to optimize the activated sludge process in such a way that NO_2^--N is converted completely to NO_3^--N. The proposed method is in fact generally applicable for nitrifying systems but was validated on a SBR. The results show that it is possible to detect the end of the NH_4^+-N oxidation during the aerobic phase of a SBR cycle by performing OUR measurements. When the NH_4^+-N oxidation rate drops to a very low level, NH_4^+-N has been completely removed. The same goes with regard to the NO_2^--N oxidation rate and the NO_2^--N concentration. For the specific case of a SBR, aeration could then be stopped and denitrification allowed to start. The use of these OUR measurements can result in aeration energy cost savings and a more constant effluent quality. In the case of an overloaded sludge for example, the aeration period could be prolonged to complete NH_4^+-N removal.

A remarkable property of the method is that not only the possibility exists to distinguish between the NH_4^+-N and NO_2^--N oxidation rate, but also the fact that the OUR data give information about COD

oxidation. This enables the operator of a SBR plant to stop aeration when all NH_4^+-N is converted to NO_2^--N (aerobic phase I). Indeed, neither COD removal nor NO_2^--N oxidation have to be completed at this moment. Denitrification works also with NO_2^- as electron acceptor (Abeling and Seyfried, 1993; Baten *et al.*, 1993). The excess COD that can still be present in the mixed liquor is useful as carbon source during the denitrification process, which results in the addition of less external carbon source for denitrification. The amount of COD present in the wastewater after completing NH_4^+-N oxidation can be estimated with the organic carbon respiration: a low activity of the heterotrophs means that the readily biodegradable COD has been converted and vice versa.

In view of the typical daily variations of the influent composition (e.g. Fig. 6) occurring in many wastewater treatment plants, the controlled phase scheduling of a SBR could allow to cope with the varying load. At higher loading, longer cycles could be established, while short cycles could be used in underloaded situations. It is evident that some storage capacity of the wastewater is needed to allow for this type of control.

Haldane competitive substrate inhibition kinetics could be extracted for NH_4^+-N oxidation rate as a function of NH_4^+-N concentration. Substrate inhibition of *Nitrosomonas* activity by NH_4^+-N can explain why in the case of an overloaded sludge (Fig. 9) the NH_4^+-N oxidation rate became higher with decreasing NH_4^+-N concentration. Substrate inhibition kinetics could not be observed for NO_2^--N oxidation rates plotted as a function of NO_2^--N concentration. This could be due to the fact that NO_2^- never reached concentrations higher than 2.5 mg NO_2^--N/l, which is still in the range of K_s for *Nitrobacter* reported by Barnes and Bliss (1983) (K_s = 0.06–8.4 mg NO_2^--N/l). Haldane K_M values can be compared with K_s values originating from normal Monod-type models. The value for K_M (1.9 mg NH_4^+-N/l) is in the range of K_s values found by Barnes and Bliss (1983) for the *Nitrosomonas* group of bacteria (K_s = 0.06–5.6 mg NH_4^+-N/l). Abeling and Seyfried (1993) also found modified Haldane kinetics, which are very similar to normal Haldane kinetics, for the conversion of NH_4^+ to NO_2^- by *Nitrosomonas*. The similarity between the results obtained with the new nitrification activity determination method and the results of other researchers corroborates the applicability of the method in practice.

CONCLUSIONS

By means of simple measurements of the OUR combined with the addition of two selective nitrification inhibitors, insight can be obtained into NH_4^+-N and NO_2^--N oxidation rates of the mixed liquor in an activated sludge system.

Changes of the nitrogen species and COD concentrations coincided well with the changes of the NH_4^+-N, NO_2^--N and COD oxidation rates. This approach shows potential for control and optimization of nitrification and aeration in biological nutrient removal processes.

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