Pergamon

Wat. Sci. Tech. Vol. 30, No. 4, pp. 169–179, 1994.

0273–1223/94 $7·00 + 0·00

0273-1223(94)00515-X

NDBEPR PROCESS OPTIMIZATION IN SBRs: REDUCTION OF EXTERNAL CARBON-SOURCE AND OXYGEN SUPPLY

Carl Demuynck*, Peter Vanrolleghem*,
Carine Mingneau**, Jan Liessens** and Willy Verstraete*

* *Laboratory of Microbial Ecology, University Gent, Coupure L. 653, B-9000 Gent, Belgium*
** *Biotim NV, Th. van Rijswijckplaats 7, B-2000 Antwerp, Belgium*

ABSTRACT

In SBR plants for nutrient removal it is often necessary to add supplementary rbCOD during the anoxic phase to obtain complete nitrogen removal. In addition to the aeration, this supply of high-quality BOD is a non-negligible part in the operating costs. Because of the complexity of the highly interconnected biological processes a heuristic approach for process optimization is hardly possible. Therefore the Nitrification Denitrification Biological Excess Phosphorus Removal (NDBEPR) model of Wentzel *et al.* and a numerical optimization algorithm were used to optimize SBR time scheduling, i.e. minimize both effluent concentrations and operating costs. It was found that a sequence of short aerobic/anoxic phases appears to be better than the usual sequence (one aerobic phase followed by one anoxic phase). This result was validated on a 500 l scale SBR. The optimized process saves up to 50% on extra BOD supply and up to 30% on aeration time. Moreover, it was shown that these cost savings were not at the expense of the phosphorus removal efficiency or the nitrification rate. From an additional numerical optimization it was seen that the ideal SBR time scheduling may depend on the loading. Therefore, a control strategy based on OUR and ORP measurements is proposed.

KEYWORDS

Activated sludge modelling; nutrient removal; optimization; process control; SBR; sensors.

INTRODUCTION

Most existing nutrient removal plants are operated in a continuous way. Several configurations rely on internal recycles to achieve good effluent quality (Henze, 1991; Pitman, 1991). Sequencing batch reactors lack this possibility and typically a reaction sequence as given in Table 1 is necessary to obtain complete removal of nitrogen and phosphorus (Norcross, 1992).

The first aerobic step must be long enough to complete phosphorus uptake and nitrification. Mostly nitrification is the limiting step. In reactors fed with wastewater having a low carbon to nitrogen ratio all BOD is normally removed before nitrification is completed. The addition of an extra carbon source (methanol, acetate, ethanol, hydrolysed sludge, ...) is then necessary to guarantee full denitrification during the anoxic step (Henze, 1992; Nyberg *et al.*, 1992).

Together with the aeration, the addition of extra COD becomes important in the running costs of such wastewater treatment plants. On the other hand it is necessary to minimize the nitrogen concentration in the effluent to protect the receiving waters and to avoid high levies.

For ecological and economical reasons it is interesting to look for a best solution, i.e. minimize the addition of extra BOD and aeration while maintaining the effluent criteria for COD and nutrients. Because the biological processes of nutrient removal are so interconnected, a heuristic approach to find optimal process operation seems hardly possible. Therefore, a model-based approach was preferred with the aid of the Nitrification Denitrification Biological Excess Phosphorus Removal model for activated sludge (NDBEPR) developed by Wentzel *et al.* (1992). Subsequently, the resulting optimal process scheme was validated on an intermediate scale SBR pilot plant and compared with the traditional SBR cycle.

MATERIALS AND METHODS

SBR cycle

To achieve nitrogen, phosphorus and BOD removal the time schedule of the different phases, given in Table 1, was devised in previous studies (Demuynck *et al.*, 1993). The total cycle time is 6 hours and 4 cycles are performed per day during normal operation.

TABLE 1. SBR Reaction Sequence for Nutrient Removal

phase	purpose	length (min)
anaerobic + filling	P release	60 + 7
aerobic 1	P uptake, nitrification, COD removal	150
anoxic	denitrification	60
aerobic 2	excess COD removal, N_2 stripping	30
settling	settling	45
decanting	decanting	15

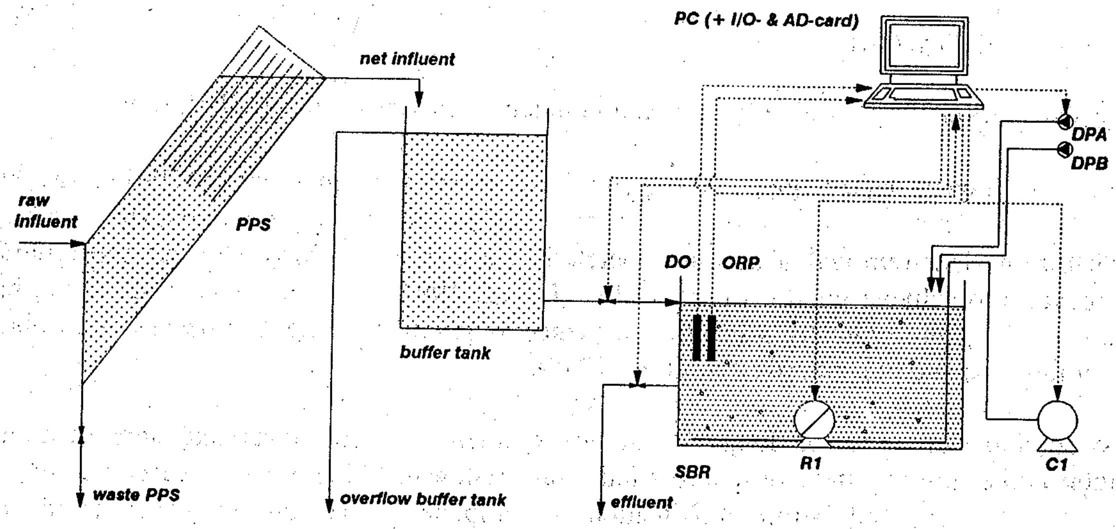

Fig. 1. Schematic overview of the SBR pilot-plant (more details, see text).

SBR pilot plant

The SBR used in the validation experiments is a 500 l reactor fed with a mixture of domestic (80%) and industrial wastewater (20%). Aeration (C1), stirring devices (R1), dosing pumps (DPA and DPB) and valves are controlled by a PC with input/output card (Figure 1). On-line measurements of dissolved oxygen (Conducta 905S) and oxidation-reduction potential ORP (Conducta PPY-DR-532) are performed by a PC with AD-card. DO and ORP electrodes are placed in a flow-through cell to avoid fouling of the sensors.

Presettling of the raw wastewater occurs in a parallel plate separator (PPS). The influent is then stored in a buffer tank where it is gently stirred to avoid further settling of the suspended matter. At the beginning of a cycle 200 l influent from the buffer tank is added to the 230 l of mixed liquor remaining after decantation.

NDBEPR model

The simulations of the biological processes in the SBR were performed with the NDBEPR model of Wentzel *et al.* (1992). This kinetic model is considered as 'the state of the art' in activated sludge nutrient removal modelling. It contains 25 processes and 19 compounds which describe the behaviour of heterotroph non-polyP, autotroph and polyP organisms under aerobic, anoxic and anaerobic conditions. It allows us to simulate nitrification, denitrification and biological phosphorus removal. Nutrient limitation is included in all growth and growth related processes.

In the differential equations a term for filling or addition of rbCOD was added (Oles *et al*, 1991):

$$\frac{dS}{dt} = r + \frac{Q}{[\,V_d + Q(t - t_d)\,]} \cdot (S_i - S) \tag{1}$$

S = reactor concentration of a model compound;
S_i = influent concentration of a model compound;
r = rate equation in NDBEPR model;
V_d = reactor volume at start of filling;
Q = influent flowrate;
t = time;
t_d = time since start of filling.

Biomass and biomass related compounds like S_{PHB} and P_{polyP} were supposed not to be present in the influent. For these differential equations, S_i was zero.

For the oxygen mass balance an additional term ($K_La.(O_{sat}$-O)) was included to account for the gaseous oxygen supply. The volumetric mass transfer coefficient K_La and the saturation concentration O_{sat} were obtained from oxygen profiles of cycles without oxygen control.

Numerical techniques

All simulations, model identifications and optimizations were performed with MOSIFIT (MOdel SImulator and FITter, a program developed at the Laboratory of Microbial Ecology and available on request). In the model identification, emphasis was given to the kinetic parameters. Most stoichiometric parameters were taken from Wentzel *et al.* (1992).

A variable step 4th order Runge-Kutta (Ralston and Wilf, 1960) was used for numerical integration. The direction set method (Brent, 1973) was preferred over the Simplex (Nelder and Mead, 1965) and Marquardt optimization algorithm (Marquardt, 1963) for its optimal trade-off between convergence speed and global convergence.

Analysis

COD, Kjeldahl-nitrogen, MLSS and MLVSS analyses were performed according to the Standard Methods (Greenberg *et al.*, 1992). A Technicon ^{TM}II AutoAnalyser was used for ammonium and nitrate analyses.

Short-time BOD and biodegradability values were obtained from the RODTOX (Rapid Oxygen Demand and TOXicity tester) (Vanrolleghem *et al.*, 1990).

Experimental design

For the validation experiments two subsequent cycles with comparable initial conditions were sampled. Both cycles were supplied with the same influent. To obtain a reproducible influent, the influent pump was interrupted at the beginning of the first cycle. By doing this the composition of the influent in the buffer tank remained constant. At the beginning of each cycle influent samples were taken to check this. The short time BOD values and biodegradability, given by the RODTOX, were an additional control.

When the reactor operates well, no ammonium is left in the reactor at the end of a cycle. However, nitrate may remain in the mixed liquor. With the following procedure zero initial nitrate concentrations could be ensured:

- first, a fast denitrification was imposed through the addition of a stoichiometric amount of acetate;
- afterwards, a short aerobic period was introduced to remove the possible excess acetate;
- concentrations of N-species were checked before filling started using Merckoquant strips.

Phosphorus removal was not taken into account for the validation experiments because preliminary experiments showed that the optimized process didn't affect the biological phosphorus removal. By omitting the anaerobic phase more rbCOD was available for denitrification, emphasizing the possible effect of the optimized aerobic/anoxic phases (see further).

TABLE 2. Estimated Parameters from the NDBEPR-model (for Nomenclature, see Wentzel *et al.*, 1992)

Biomass fraction	Parameter	Literature	Experimental	Units
Non-polyP heterotrophs	μ_H	0.001 - 0.0025	0.00117	/min
	K_{SH}	5.0	32.9	g COD/m^3
	K_{MP}	0.00095	0.000318	g COD/g cell COD.min
	K_{SP}	0.027	0.0997	g COD/g cell COD
	K_A	0.000118	0.0000280	g COD/g cell COD.min
	K_R	0.000022	0.000250	m^3/g cell COD.min
	K_C	0.000028	0.0000107	m^3/g cell COD.min
	nu_G	0.33 - 0.6	0.62	-
Autotrophs	μ_A	0.00014-0.0005	0.000276	/min
	K_{SA}	1.0	0.824	g NH4-N/m^3
	Y_{ZA}	0.666	0.234	g cell COD/g NH4-N
PolyP organisms	μ_{GI}	0.00083	0.0016	/min
	K_{SGI}	0.18	0.0379	g COD/m^3
	f_{Pupt}	0.75	0.474	
	K_P	0.0042	0.00236	g COD/g cell COD.min

RESULTS AND DISCUSSION

Model identification

For the estimation of the model parameters, experimental data were used obtained from a SBR cycle which was sampled in detail (soluble and total COD, Kj-N, ammonium, nitrate and phosphate of influent and effluent; ammonium, nitrate and phosphate in the mixed liquor at regular intervals during the cycle; MLSS and MLVSS of the sludge). The oxygen supply was not controlled so that additional information was available for calculation of oxygen uptake rates, K_La and O_{sat} values.

Table 2 gives an overview of the parameters that were estimated. Most of the estimates are in the same order of magnitude as the values mentioned by Wentzel *et al.* (1992). It is obvious that a lot of the parameters will change when the initial biomass concentrations in the reactor are not measured or estimated correctly. In the rate equations of the different substrates the biomass is directly linked with e.g. the growth rate and cannot be identified separately. Still, the combination of these parameters is estimated reliably for the purposes of this work. The different biomass fractions were estimated starting from MLVSS in the reactor and literature values (Henze, 1992).

The rate of particulate hydrolysis, K_R, was about ten times higher than the value mentioned by Wentzel *et al.* (1992). The stoichiometric parameter that relates the phosphorus uptake with the growth of the polyP organisms (f_{Pupt}) was found to be more or less equal to the phosphorus release factor (f_{Prel}). This could mean that the excess phosphorus uptake was only due to newly formed polyP biomass. The literature value for f_{Pupt} was the only stoichiometric parameter, next to the autotrophic yield Y_{ZA}, that had to be adjusted to be able to describe the experimental findings.

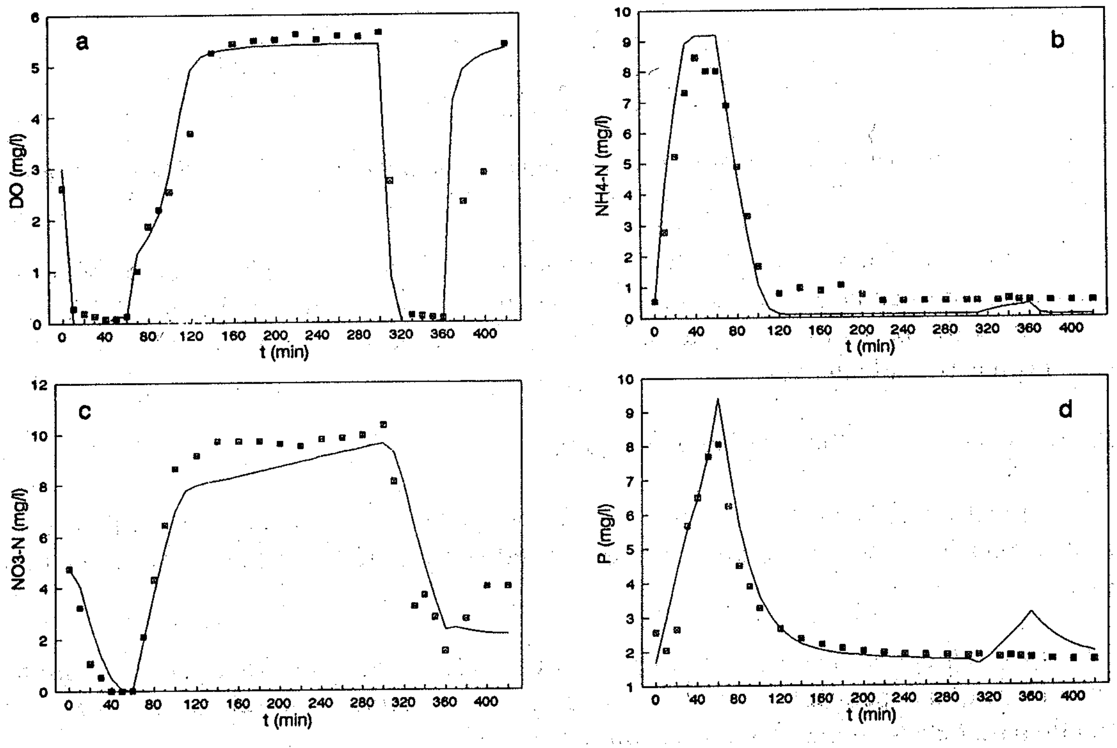

Fig. 2. Experimental and simulated data of a SBR cycle (a: oxygen; b: ammonium; c: nitrate; d: phosphorus)

Figure 2 shows the fit between the model predictions and the experimental data. Considering the dynamics of a SBR system, the simulated values agree quite well with the experimental observations. The most remarkable deviation concerns the significant P-release during the anoxic phase, caused by excessive maintenance polyP cleavage.

It must be mentioned that due the complexity of the model, reflected in the high number of parameters and state variables, it is not always straightforward to obtain a reasonable fit of the model to the restricted dataset.

Optimization of the process

The NDBEPR-model with the parameter set given in Table 2 was used to find an optimal process scheduling. The degrees of freedom were the number of subsequent aerobic/anoxic phases and the length of the phases. The following constraints were imposed: the length of aerobic and anoxic phases is equal for all phases and the total time of the cycle should not exceed the time necessary for the traditional one. The initial anaerobic and the final aerobic phase were retained.

The objective function J consisted of two major terms: (1) the effluent concentrations of COD, ammonium, nitrate and phosphorus should be as low as possible and (2) the oxygen supply and the addition of supplementary COD should be minimized. The result of the process optimization is shown in Figure 3.

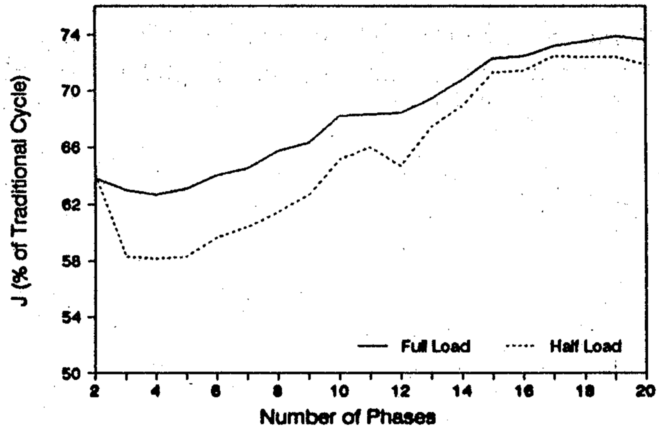

Fig. 3. Results of the minimization of the objective function J: J vs. number of the short aerobic/anoxic phases (100% = traditional cycle)

It can be clearly observed that a cycle with short subsequent aerobic/anoxic phases gives better results than the traditional cycle. This can be easily understood: when the aeration is stopped before all COD is removed, the nitrate formed in the previous phase can be removed with the influent COD instead of an additional COD-source. This has two advantages:

- less extra COD is needed for complete denitrification;

- from an economical point of view it is better to remove influent COD under anoxic than under aerobic conditions, since oxygen immobilized in the nitrate formed is recovered, with a concommittant reduction in aeration costs.

The idea is thus to redirect as much influent COD as possible to the denitrification. The minimum in the objective function was independent of the loading (figure 3). A study is, however, required to assess the impact of kinetic parameters on the optimal scheduling.

Validation

In order to validate this result some pilot scale experiments were performed. For practical reasons the sampled cycles were run without a preliminary anaerobic phase (same initial conditions, see before). By omitting the anaerobic phase all influent rbCOD could be used in the aerobic/anoxic phases so that a better comparison was possible between the traditional and the optimized process.

In the first validation experiment the traditional cycle (150 min. oxic/60 min. anoxic) and the optimized cycle (5 times 21 min. oxic/21 min. anoxic) were compared. Figure 4 shows the ammonium and nitrate profiles of both cycles.

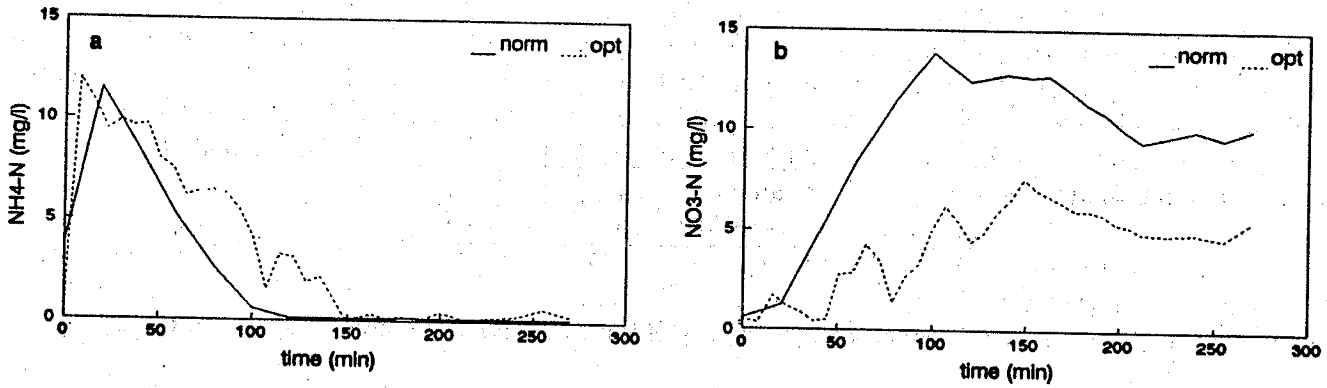

Fig. 4. NH_4-N profile (a) and NO_3-N (b) profile of traditional and optimized SBR cycle.

In both cycles the ammonium concentration started to decrease to zero as soon as the filling finished. In the optimized process this went slower due to the inserted anoxic phases, in which no ammonium removal occurred.

The nitrate effluent concentration was approximately 50% lower in the optimized cycle (5 mg/l vs. 10 mg/l). This can be translated to the amount of extra carbon source that is required to remove the residual nitrate, i.e. for complete N-removal 50% less rbCOD would be needed.

The denitrification rate in the traditional cycle (0.054 mg N/l.min) depends on the hydrolysis of particulate COD and was rather slow in comparison with the denitrification rates of the second (0.202 mg N/l.min) and third (0.128 mg N/l.min) anoxic phases of the optimized cycle (in the first aerobic phase almost no nitrate was formed, so the first anoxic phase was not taken into account). The higher denitrification rates can be explained by the presence of readily biodegradable influent COD. The fourth (0.058 mg N/l.min) and fifth (0.028 mg N/l.min) anoxic phases gave more or less the same denitrification rate as compared to the traditional cycle. At this stage of the cycle the denitrification rate was probably also limited by the hydrolysis of particulate COD.

This comparison of the denitrification rates clearly shows the potential of a better use of influent COD and also points to the possibility of an increased degradative capacity for the optimized operation of a SBR. However, the last two anoxic phases indicate that still some, but less, supplemental rbCOD will be needed for complete nitrogen removal.

An important goal of the validation experiments was to show that the other nutrient removal processes didn't suffer from this new operation mode. Figures 4 and 5 illustrate that nitrification rates are not affected by the inserted anoxic phases.

SBR cycles with an anaerobic phase included showed that the optimized sequence didn't affect the biological phosphorus removal (Figure 5). No phosphorus release was detected during the switching aerobic/anoxic phases and the average phosphorus concentration was below 1 mg/l. Remark that the dissolved oxygen was controlled at 2.0 mg/l with a dead-band of 0.5 mg/l.

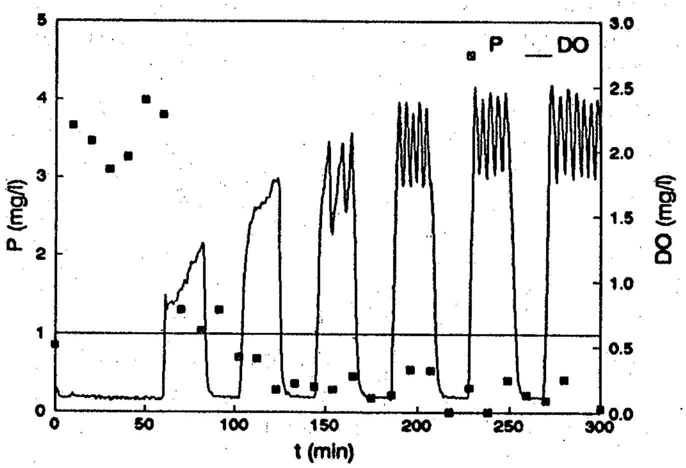

Fig. 5. Phosphorus and oxygen profile in an optimized SBR cycle.

In a second experiment a comparison was made between an optimized cycle with constant length of the aerobic and anoxic phases (cfr. first experiment) and a cycle with varying lengths of the phases, i.e. long aerobic and short anoxic phases in the beginning, short aerobic and longer anoxic phases at the end of the cycle. This setup was chosen heuristically on the basis of the finding in the first experiment that the denitrification goes fast at the beginning of the cycle, slowing down at the end of the cycle. Keeping the nitrate removal per anoxic phase more or less constant was the aim of the experiment, meaning that the length of the anoxic phases had to increase as the SBR cycle progressed. At the same time, the length of the oxic phase was decreased to keep the length of each oxic/anoxic combination constant.

The experimental results of figure 6a show that the ammonium concentrations in the effluent were more or less identical for both operating procedures. The results for nitrate were not better in the cycle with varying length of the phases in spite of the increasing length of the denitrification phase at the end of the cycle (figure 6b).

To study this unexpected result in more detail, a second numerical optimization was initiated with the following degrees of freedom: the number of subsequent aerobic/anoxic phases, the initial length of the phases and the slope which determines the decrease or increase in length of the aerobic and anoxic phases while the SBR cycle progresses. The length of each aerobic/anoxic combination however was not allowed to change. The initial anaerobic and final aerobic phases were not altered. From the results of this optimization the following trends could be deduced:

1) the slope should be as high as possible, i.e. short anoxic phases in the beginning of the cycle and long anoxic phases at the end of a cycle;

2) the total length of the anoxic phase should be somewhat higher than the total length of the oxic phases, but the actual lengths depend on the loading rate (with low loading rates, a longer anoxic period is better);

3) lower numbers of switching oxic/anoxic phases give better results.

In the above experiment, the first trend was incorporated, but the second trend couldn't be derived heuristically and that is probably the explanation for the poorer results of the second experiment.

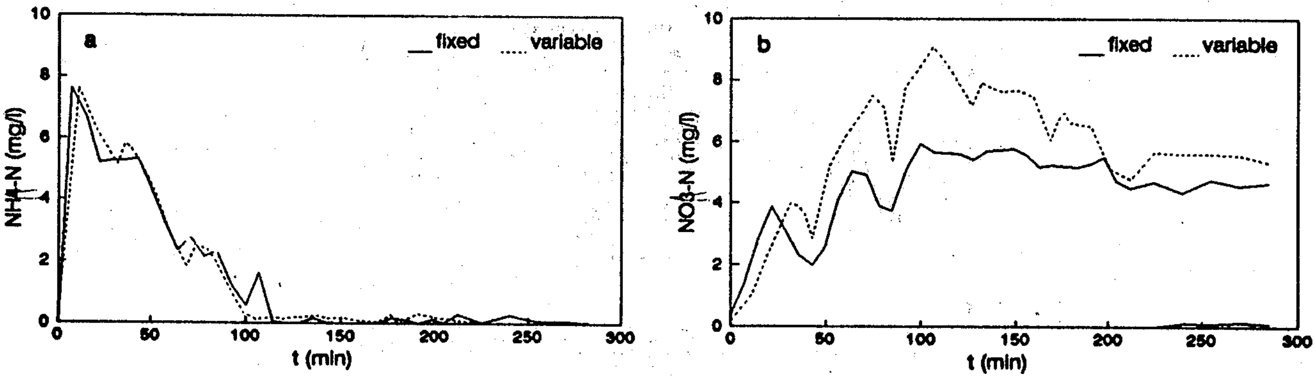

Fig. 6. NH_4-N (a) and NO_3-N (b) profile in a cycle with fixed (5 times 21 min oxic/21 min anoxic) and a cycle with varying length of the oxic/anoxic phases (starting with 31 min oxic/11 min anoxic and ending with 11 min oxic/31 min anoxic)

Proposal for control of SBR time scheduling

It was seen that it is indeed possible to improve the SBR nutrient removal process with the aid of an activated sludge model, but the numerical optimization also indicated that a "preset" time schedule is not ideal because different loading rates can lead to different optimal time schedules. Therefore, adaptation of the SBR time scheduling is required. On-line oxygen and ORP measurements can give the information needed: ORP measurements can be used to detect the end of denitrification by the so-called 'nitrate-knee' (figure 7) (Wareham *et al.*, 1993). From that point on it has no sense to maintain the anoxic conditions since they could eventually lead to conditions where P-release can occur. As soon as the nitrate-knee is detected, aeration can be switched on.

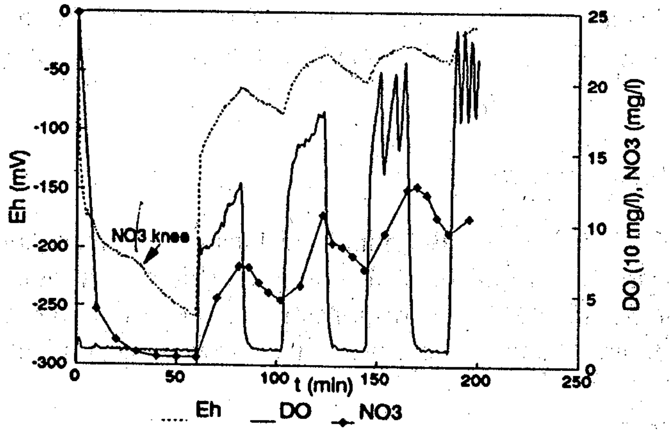

Fig. 7. ORP profile with 'nitrate-knee'.

Figure 8 illustrates the potential use of oxygen profiles from a SBR cycle for control strategies. Oxygen was controlled at 2 mg/l with an on/off control with dead-band. The time between switching off and switching on of the aeration device during the aerobic phases is a measure for the oxygen uptake rate. When nitrification is completed OUR drops as can be observed in the oxygen profile (figure 8). Hence, this information can be used to control the aeration system.

By combining these two on-line measurements a control strategy can be developed. The lengths of the different phases and the total cycle time can be adapted on-line so that a maximum nutrient removal is combined with an efficient oxygen supply and COD use. This procedure will have two advantages. Both effluent concentrations and operating costs will be reduced. Moreover, the loading of such a SBR can be increased since no (or lower) safety factors must be included in the process operation.

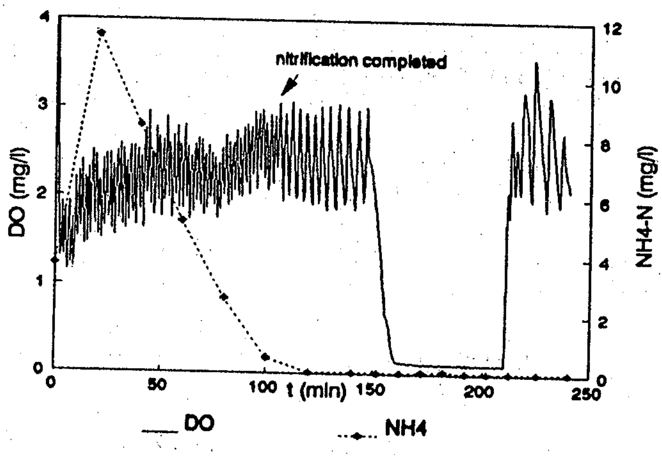

Fig. 8. Oxygen and ammonium profile of a SBR cycle

CONCLUSIONS

Simulation of the nutrient removal processes in a SBR reactor has been successful using the NDBEPR model of Wentzel *et al.* (1992). Due to the high number of parameters in the model compared to the amount of data, identification was not straightforward. Eventually, however, a reasonable model fit was obtained.

With this model and a numerical optimization algorithm, it was possible to improve the SBR time sequence. A cycle with a sequence of several shorter aerobic and anoxic phases allowed us to reduce both oxygen and extra rbCOD supply while maintaining good nutrient removal. The biological P-removal wasn't affected by this alternative time sequence.

These results were validated on a SBR pilot plant. However, additional simulation results in which the effect of the loading was assessed, clearly pointed to the need for a control of the SBR phase scheduling to maintain optimal performance at minimal costs. A control strategy based on oxygen and ORP measurements was proposed.

ACKNOWLEDGEMENTS

The cooperation with Biotim NV (Antwerp, Belgium) and Janssen Pharmaceutica NV (Beerse, Belgium) is greatly appreciated. This research is part of the VLIM program (Flemish Impuls Program for Environmental Technology), initiated by the Flemish Minister responsible for the environment. The authors would like to thank Paul Willems for developing the basic structure of the software used to control the SBR.

REFERENCES

Brent, R. P. (1973). *Algorithms for Minimization without Derivatives*, Prentice-Hall, Englewood Cliffs, New Jersey. pp. 195.

Demuynck, C., Vanrolleghem, P., Mingneau, C., Liessens, J. and Verstraete, W. (1993). Optimal BOD use and oxygen supply in a sequencing batch reactor for nutrient removal, In: *Proceedings Workshop on Modelling, Monitoring and Control of Wastewater, Treatment Processes*, Med. Fac. Landbouww. Rijksuniv. Gent, 58, (accepted).

Greenberg, A., Clesceri, L. and Eaton, A. (1992). *Standard Methods for the Examination of Water and Wastewater*, 18th edition, American Public Health Association, Washington DC.

Henze, M. (1991). Capabilities of biological nitrogen removal processes from waste water. *Wat. Sci. Tech.*, **23**(4-6), 669-679.

Henze, M. (1992). Characterization of wastewater for modelling of activated sludge processes. *Wat. Sci. Tech*, **25**(6), 1-15.

Marquardt, D. W. (1963). An algorithm for least squares estimation of nonlinear parameters, *J. Soc. Ind. Appl. Math.*, **11**, 431-441.

Nelder, J. A. and Mead, R. (1965). A simplex method for function minimization, *Comp. J.*, **7**, 308-313.

Norcross, K. L. (1992), Sequencing batch reactors – An overview, *Wat. Sci. Tech.*, **26**(9-11), 2523-2526.

Nyberg, U., Aspegren, H., Andersson, B., Jansen, J. la C. and Villadsen, I. S. (1992). Full-scale application of nitrogen removal with methanol as carbon source, *Wat. Sci. Tech.*, **26**(5-6), 1077-1086.

Oles, J. and Wilderer, P. A. (1991). Computer aided design of sequencing batch reactors based on the IAWPRC model. *Wat. Sci. Tech.*, **23**(4-6), 1087-1095.

Pitman, A. R. (1991). Design considerations for nutrient removal activated sludge plants, *Wat. Sci. Tech.*, **23**(4-6), 781-790.

Ralston, A. and Wilf, H. S. (1960). *Mathematical methods for digital computers*, Wiley, New York, 110-120.

Vanrolleghem, P., Dries, D. and Verstraete, W. (1990). RODTOX: Biosensor for rapid determination of the biochemical oxygen demand and the on-line monitoring of the toxicity of wastewaters, In: *Proceedings Fifth European Congress on Biotechnology*, Copenhagen, Denmark, July 8-13 1990. Vol. 1, 161-164.

Wareham, D. G., Hall, K. J. and Mavinic, D. S. (1993). Real-time control of wastewater treatment systems using ORP. *Wat. Sci. Tech.* **28**(11-12), 273-282.

Wentzel, M. C., Ekama, G. A. and Marais, G. V. R. (1992). Processes and modelling of nitrification denitrification biological excess phosphorus removal systems – A review, *Wat. Sci. Tech.*, **25**(6), 59-82.