Model-based evaluation of an on-line control strategy for SBRs based on OUR and ORP measurements

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Abstract Application of control strategies for existing wastewater treatment technologies becomes necessary to meet ever-stricter effluent legislations and reduce the associated treatment costs. In the case of SBR technology, controlling the phase scheduling is one of the key aspects of SBR operation. In this study a calibrated mechanistic model based on the ASM1 was used to evaluate an on-line control strategy for the SBR phase-scheduling and compare it with the SBR's performance using no control strategy. To evaluate the performance, reference indices relating to the effluent quality, the required energy for aeration and the treated wastewater volume were used. The results showed that it is possible to maintain optimal SBR performance in the studied system at minimal costs by on-line control of the length of the aerobic and anoxic phases.

Keywords Denitrification; modelling and calibration; nitrification; process control; SBR operation

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Introduction

One of the advantages of sequencing batch reactor (SBR) technology in comparison to traditional biological treatment processes is that it is capable of handling wide fluctuations in hydraulic and organic loadings (Mace and Mata-Alvarez, 2002). Normally these systems work with a fixed cycle configuration which is repeated over time, obtained through the experience of the operators. The predetermined cycle is sometimes not able to adapt to dynamic changes in the influent, leading to excess resources being used. The correct choice of environmental conditions in the SBR systems lead to the oxidation of organic matter and nitrogen removal divided into nitrification (ammonia oxidation to nitrate) and denitrification (nitrate depletion to gas nitrogen). Controlling the alternating aerobic and anoxic phases is essential for eliminating nitrogen and phosphorous (Andreottola *et al.*, 2001; Sin *et al.*, 2004). Since stricter legislation is now being applied, more control over wastewater treatment systems is needed particularly in the interest of reducing costs.

The interest in developing on-line sensor-based control schemes has increased in recent years due to the ease of implementation. In this sense, dissolved oxygen (DO), pH and oxidation reduction potential (ORP) signals have been used to determine the end-points of the nitrification and denitrification reactions (Chang and Hao, 1996; Yu *et al.*, 1998; Kishida *et al.*, 2003), allowing the length of each alternating aerobic and anoxic phases to be adjusted. This results in an optimised cyclic operation of the SBR system that provides better effluent concentrations and cost savings.

There are many ways to manage optimal operation of SBR technologies, which are expensive and time-consuming to test experimentally. Using a model-based evaluation represents an advantage when defining and evaluating the control strategies. Different mathematical models and simulators have been proposed and used for process design,

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performance evaluation or control of activated sludge systems (Demuynck *et al.*, 1994; Vanrolleghem and Coen, 1995; Sin *et al.*, 2004).

The research presented in this paper relies on an on-line control strategy designed and applied to an experimental pilot plant SBR in a previous study. Depending on the influent concentrations, it was possible automatically to adjust the phase length without affecting effluent quality (Corominas *et al.*, 2004; Puig *et al.*, 2005, 2006). The purpose of this paper is to improve the control strategy through model-based evaluation. This enables the easy testing of different possibilities of control and evaluation of the performance in terms of effluent quality, energy requirements and plant capacity.

Materials and methods

Plant description

The SBR consisted of a cylindrical reactor with maximum and minimum working volumes of 30 and 20 L, respectively. To achieve complete nitrogen removal in the SBR, the hydraulic retention time (HRT) and solids retention time (SRT) were maintained at 0.8 days and 18 days, respectively.

An eight-hour cycle time divided into a reaction phase (395 min), a settling phase (60 min) and a draw phase (25 min) was used for the entire experimental study (see Figure 1). A cycle with a six step-feed strategy and alternating anoxic and aerobic phases was defined by previous studies to achieve organic matter and nitrogen removal (Puig *et al.*, 2004; Vives *et al.*, 2004).

Model development and calibration

Calibration was conducted in WEST software following the stepwise procedure of the BIOMATH protocol (Vanrolleghem *et al.*, 2003; Sin, 2004) and the parameters were transferred into GPS-X. A profile of one cycle (480 min) taken from Vives *et al.* (2004) was used for the calibration. The ASM1 (Henze *et al.*, 2000) was used to describe the biological reactions in the SBR. The target of the calibration was to obtain a model to support the definition of the optimal cycle operation basically focused on carbon and nitrogen removal. For this purpose the model was expected to describe the ammonia, the oxidised nitrogen and also the oxygen dynamics during one SBR cycle. Special effort was made with the oxygen profile, and especially in calibrating the oxygen mass transfer coefficient, K_La, value. A correction of the K_La was applied as a function of the changing volume of the reactor. The calibration was conducted using a set of data from the SBR operation with no DO control, since that gives more information about the process rates, and therefore improves the accuracy of the calibration of the oxygen dynamics in the system. All calibrated parameter values were in the range reported in the literature (e.g. Henze *et al.*, 2000; Sin, 2004). The calibration results of the reaction phase are shown in Figure 2. It can be seen that the simulated data fit the experimental values well. More details of the model calibration can be found in Corominas *et al.* (2005).

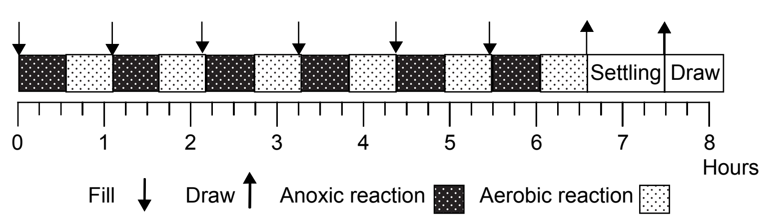

Figure 1 SBR cycle configuration with step feed strategy

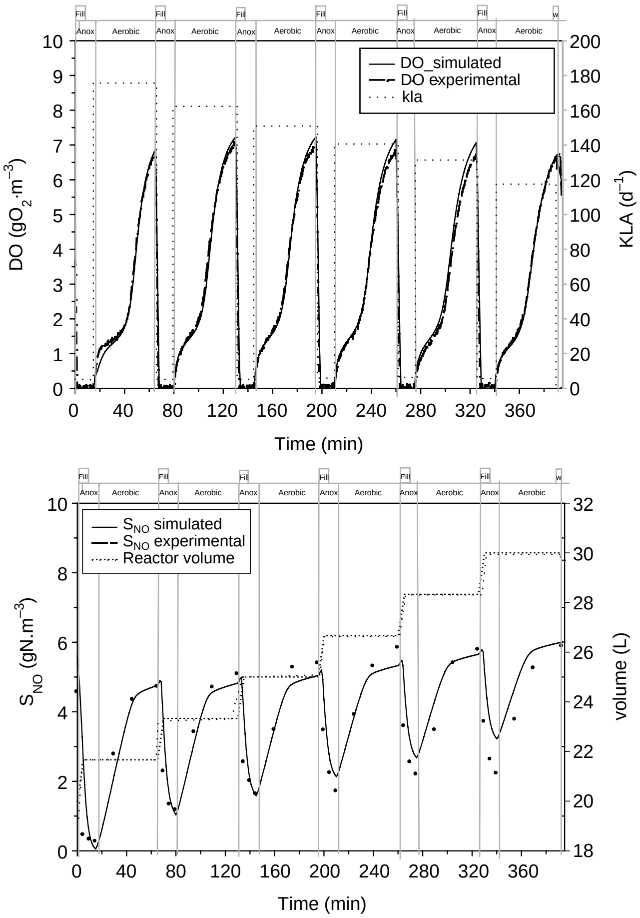

Figure 2 Model calibration results for oxygen (top) and for nitrate (bottom) dynamics in the SBR

Model-based implementation of the control strategy

Simulations were run for seven days with varying influent data, but with a constant influent flow. The time interval was set at 10 sec, which was the time established for action for the experimental pilot plant dissolved oxygen on/off controller. A first-order delay of 30 s in the DO variable was considered in the simulations to account for the delay observed in the DO probe of the experimental pilot plant. The plant performance was assessed by the average effluent suspended solids concentration (TSS), COD, total nitrogen (TN), BOD_5 and wastewater flow (Qe), to calculate the effluent quality index, EQ (adapted from Copp, 2001) and presented in equation (1). As the length of the phases is different in each cycle and this influences the amount of water treated, the EQ index was also expressed as a function of the cubic metres of treated water (*Vt*).

$$EQ = \frac{1}{1000\,T\,Vt}\int_{1}^{T}[2\,TSS(t) + COD(t) + 20\,TN(t) + 2\,BOD_5(t)]\,Qe(t)\,dt \qquad (1)$$

For the aeration energy the index aeration energy required of GPS-X was used (Hydromantis, 2003) and referred to the volume of treated wastewater. The power requirement is calculated using equation (2):

$$\text{Energy} = \frac{\dfrac{\text{airflow}}{86.4 \cdot 10^7} \cdot \text{headH}_2\text{Odens}}{\text{pumpeff}} \qquad (2)$$

where Energy is the aeration energy required ($kW\,h\,d^{-1}\,kgCOD^{-1}$), airflow is calculated from the K_La (m^3/d), head is the hydraulic head (m), H_2Odens is the density of water ($N\,m^{-3}$) and pumpeff the pump efficiency (unitless).

Results and discussion

Development and conceptual background of the control strategy

The correct definition of on-line control strategies is of great importance in successfully optimising the SBR performance. Optimal phase scheduling can be based on detecting the endpoints of the nitrification and denitrification processes. Based on expert knowledge and with the help of a calibrated model, different control strategies based on oxygen uptake rate (OUR) and ORP measurements can be proposed and evaluated before their implementation in pilot plant or full-scale systems (Puig *et al.*, 2005).

When dealing with aerobic phases the end of nitrification can be determined using on-line sensors. In this sense the α point can be detected in the DO probe signals and the Ammonia Valley in the pH signals (Kishida *et al.*, 2003). When a DO controller is used (on/off, PID, fuzzy), the DO signals alone do not provide directly meaningful information for the on-line control strategy. Nevertheless, the direct calculation of the OUR from the DO measurements is a good indicator of the state of the process (Copp *et al.*, 2002). Practical application of OUR estimation and expert knowledge extraction from on-line measured variables for the optimisation of an SBR cycle is presented in Puig *et al.* (2006).

Figure 3 presents the evolution of simulated OUR, ammonia (S_{NH}), derivative of OUR and the sum of nitrites and nitrates (S_{NO}) for an 8 hour SBR cycle using an on/off DO controller during the aerobic phases.

Considering the OUR values at the beginning of the aerobic phase, a fast increase in the OUR is observed because the rates of heterotrophic growth and autotrophic growth were high. As soon as the ammonia is depleted (see Figure 3, circles), a drop in the OUR

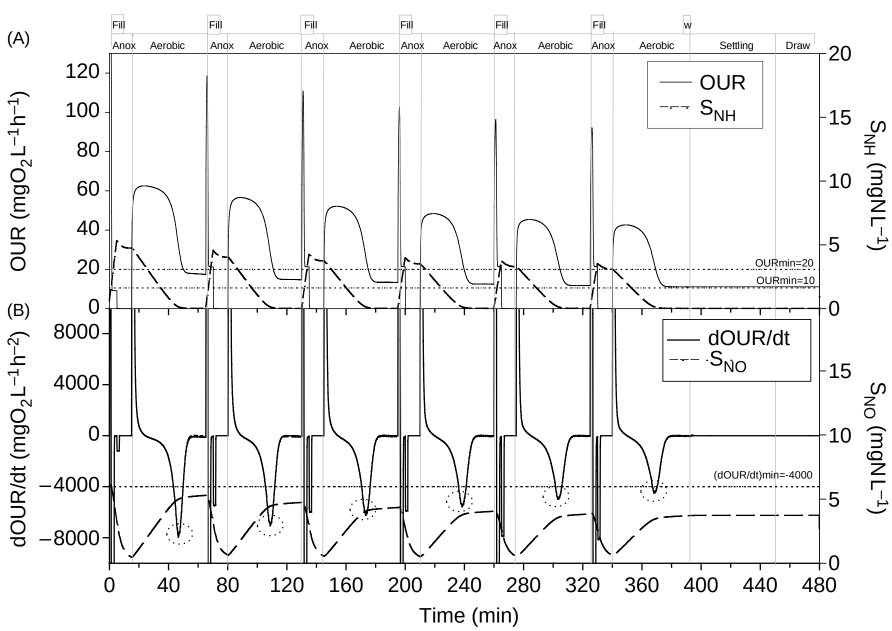

Figure 3 (A) Evolution of simulated OUR and ammonia (S_{NH}), (B) evolution of OUR derivative and the sum of nitrate and nitrite (S_{NO}) concentrations, during an eight hour cycle

profile can be observed. After that, the OUR profile remains constant which indicates that the system is under endogenous conditions. An on-line control strategy based on OUR measurements would therefore be able to adjust the length of aerobic phases when the OUR reaches a minimum value, OUR_{min}, which is related to endogenous conditions. Thus, because OUR_{min} diminishes over the reaction phase because of dilution of the sludge as the volume increases, depending on the OUR_{min} value selected, the control strategy will affect all the aerobic phases or just the last ones when the OUR reaches lower values.

A better approach is possible if the on-line control strategy is able to adjust all the aerobic phases. Detecting this phenomenon is possible with the OUR derivative. In Figure 3(B), an on-line control strategy based on the filtered (moving average of 10 data points) derivative of the OUR is presented. At the beginning of the aerobic phase the derivative is very high due to the sharp increase in the OUR values. When the OUR starts to decrease the derivative goes to negative values, reaching a minimum. The minimum in the derivative coincides with the complete depletion of ammonia. A first approach could be to change to the next phase when the minimum in the derivative is exceeded.

On the other hand, the anoxic phases can also be adjusted. To determine the end of anoxic phases pH (nitrate apex) and/or ORP (nitrate knee) measurements can be applied. As the model cannot predict these measurements, as soon as the oxidized nitrogen (S_{NO}) concentration reaches a minimum value the system can change to the next phase.

In this study different strategies have been tested on a calibrated model:

(1) No control strategy without an on/off DO controller;
(2) No control strategy with an on/off DO controller;
(3) Three different control strategies based on a minimum OUR and a minimum ORP, i.e. simulated as the sum of nitrite and nitrate.

A scheme of the on-line control strategy is presented in Figure 4. For the control strategy, a minimum time (t_{min}) for the phases is defined for two reasons: first, to avoid false minimum OUR points at the beginning of the phases, and second to avoid premature aerobic phase ending caused by the transient response of the activated sludge from the sequence of intracellular reactions involved in substrate degradation by activated sludge (Vanrolleghem *et al.*, 2004). A maximum phase time (t_{max}) is also defined so as to keep working with the predetermined cycle definition. When the OUR_{min} or the $S_{NO,min}$ have

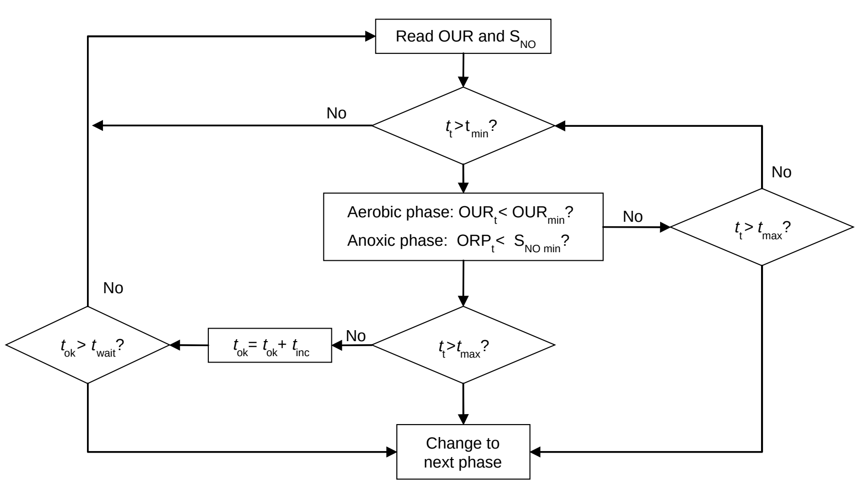

Figure 4 Scheme of the on-line control strategy

been exceeded, a waiting time (t_{wait}) is applied to avoid detection errors due to possibly incorrect measurements, and then the system changes to the next phase.

Model-based evaluation of different control strategies

Having defined the possible strategies to improve the SBR performance, the next step was to test them using the calibrated model. The results of the EQ, the aeration energy (AE), and the treated wastewater volume (*Vt*) for the different strategies are presented in Table 1.

The importance of implementing an on/off DO control can be seen in the EQ and AE indices. When an on/off DO controller is used (No. 2, Table 1), the EQ decreases from $0.0298\,\mathrm{kg\,d^{-1}\,L^{-1}}$ to $0.0188\,\mathrm{kg\,d^{-1}\,L^{-1}}$, which represents a 37% reduction in pollution. This decrease is mainly related to the effluent nitrogen concentration, which has a high weight (20) in the EQ calculation from equation (1). Controlling the DO at a certain low level means not having an excess of DO in the system and the anoxic reaction time is increased, improving the denitrification process with a reduction in the nitrite and nitrate concentration in the effluent. The cost savings related to the aeration energy used represent a 27% reduction (from 0.1916 to $0.13975\,\mathrm{kW\,h\,d^{-1}\,L^{-1}}$) compared with the reference system with no control strategy (No. 1, Table 1).

The major improvements from implementing the on-line control strategy are related to the AE index and the capacity of the plant. The results suggest it is possible to obtain a reduction of 35% in the aeration energy used (No. 5, Table 1), compared with the uncontrolled conditions (No. 1, Table 1). In addition, the capacity of the plant is increased, which means that the treated wastewater volume could be increased up to 35% or that the required volume of the reactor could be reduced. All these improvements can be achieved without affecting the quality of the effluent. This is shown by the EQ index, which is near the values obtained with the simple on/off DO control (No. 2, Table 1), and also by the effluent concentration values which are always within the discharge limits of the European Directive 92/271/CEE.

Possible limitations of proposed methodology

Figure 5 shows the evolution of the simulated data profile obtained with the on-line control strategy and a DO On/Off controller. It can be seen that the total cycle length of the SBR has been reduced by 21% of the cycle, with considerable cycle optimisation.

It is important to recall that in this study a model-based approach is followed to evaluate the system behaviour under different control strategies. From a practical application point of view, it is known that model-based optimisation and control of activated sludge systems usually leads to changes in the microbial community of the system (Yuan and Blackall, 2002; Sin *et al.*, 2005). This may in turn shift the behaviour of the system beyond the validity domain of the model (Sin *et al.*, 2006). Nevertheless, Sin *et al.* (2006) also showed that, although the model became invalid, the operation strategy which was developed by

Table 1 Performance indexes for evaluating the control strategies

On-line control strategy			DO control	EQ ($\mathrm{kg\,d^{-1}\,L^{-1}}$)	AE ($\mathrm{kW\,h\,d^{-1}\,L^{-1}}$)	*Vt* (L)
No.	OUR_{min} ($\mathrm{mgO_2\,L^{-1}\,h^{-1}}$)	$S_{NO,min}$ ($\mathrm{mgN\,L^{-1}}$)				
1	–	–	No	0.0298	0.1916	210
2	–	–	on/off	0.0188 (37%)	0.1397 (27%)	210
3	10	0.2	on/off	0.0184 (38%)	0.1377 (28%)	226 (7.5%)
4	20	0.2	on/off	0.0180 (39%)	0.1249 (35%)	279 (33%)
5	20	0.5	on/off	0.0179 (40%)	0.1251 (35%)	284 (35%)

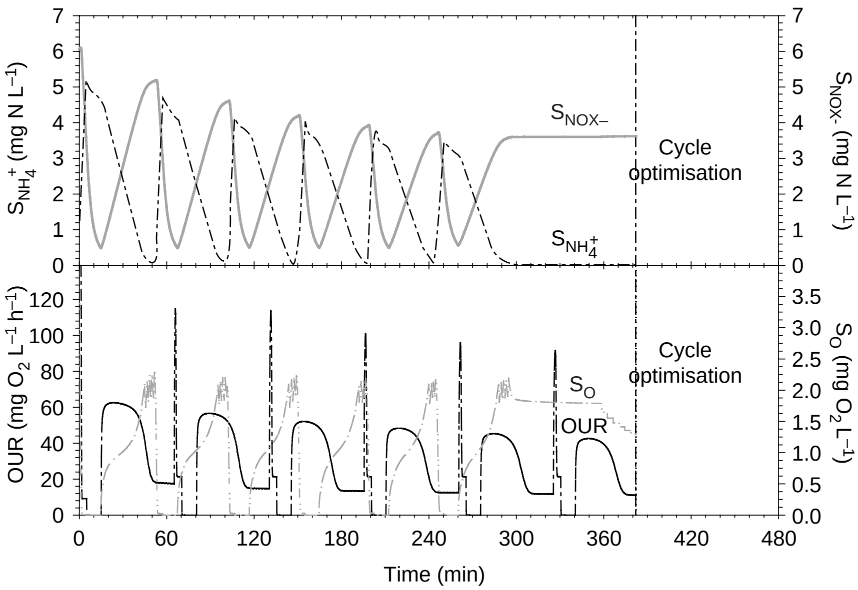

Figure 5 Simulated data profile applying an on-line control strategy and On/Off DO controller

the model still produced better results for nitrogen removal in reality than the model had predicted. The underlying reason for this loss of validity was attributed to the inability of the models used to account for changes in the microbial community under quite different operational conditions (Sin *et al.*, 2006). On the other hand, in order to adapt the model adjustment to microbial community changes, a recalibration protocol must be considered when model-based optimisation and control is planned to be used. Since the reported experience of Sin *et al.* (2006) could be case specific, the proposed control strategy in this study will be implemented and evaluated in reality to extend the experiences with model-based control of SBR technology.

Conclusions

In this study, a model-based approach was used for the development and evaluation of control strategies to improve the effluent quality and reduce the associated treatment costs, in particular, the aeration energy costs. The results of the simulations suggest that implementing a DO controller improves the denitrification process, leading to a reduction in the nitrite and nitrate concentration in the effluent. The on-line control strategy using OUR and S_{NO} appeared to be useful for adjusting the cycle length of the reaction phases in the SBR technology, reducing the required aeration energy up to 35% and considerably increasing the plant capacity. However, care should be exercised when interpreting these promising results, since the new operation and control may change the system to an extent where the model may no longer hold. This issue will be verified by implementing the on-line control strategy in the pilot plant SBR.

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