10th International IFAC Symposium on
Computer Applications in Biotechnology
Preprints Vol.2, June 4-6, 2007, Cancún, Mexico

AUTOMATION OF THE ACCLIMATION PHASE IN A SEQUENCING BATCH REACTOR DEGRADING INHIBITORY COMPOUNDS

Alejandro Vargas * **Francisco Velarde** *
Germán Buitrón *

* *Bioprocesos Ambientales, Instituto de Ingeniería,
Universidad Nacional Autónoma de México,
Circuito Escolar s/n, Ciudad Universitaria, 04510
Coyoacán, D.F., Mexico*

Abstract: An automatic strategy for acclimation of biomass to 4-chlorophenol in a sequencing batch reactor was evaluated. It combines an I/O linearizing plus PID controller to regulate the dissolved oxygen within the reactor at a given setpoint using the airflow rate, and a simple algorithm for establishing the end of the reaction phase using the manipulated airflow signal. The strategy was tested experimentally, obtaining results that indicate that itis a viable alternative for automatic acclimation of biomass for toxic wastewater treatment in a SBR.

Keywords: Acclimation, dissolved oxygen control, wastewater treatment, PID control, SBR

1. INTRODUCTION

Industrial wastewater containing toxic organic compounds is difficult to treat by conventional biological wastewater treatment processes, due to several factors that include the variability of the wastewater flow and composition, as well as the presence of compounds that may be inhibitors to the microorganisms under relatively low concentrations. However, sequencing batch reactors (SBR) have been shown to be a viable alternative (Wilderer *et al.*, 2001).

A sequencing batch reactor operates in five well defined phases: fill, react, settle, draw, and idle. During the first phase the reactor is filled from a minimal volume to an operating volume as fast as possible. Next, during the reaction phase enough time is allowed for the microorganisms to completely biodegrade the compounds to be treated. After this, a settling phase is started and afterwards a draw phase removes the treated supernatant. Finally an idle phase is allowed before starting the next cycle.

The first step to biodegrade toxic substances in a wastewater treatment plant is the acclimation of the microorganisms. Different mechanisms have been described to explain the acclimation phase and in aerobic microbial communities, it ranges from several hours to several days (Wiggings *et al.*, 1987). It has been shown that a suitable acclimation strategy, where the reaction phase is stopped as soon as degradation has occurred, produces a microbial community with higher specific activity and excellent sludge characteristics even after long term operation (Moreno and Buitrón, 2004). Such an acclimation strategy implies continuous monitoring of the substrate concentration within the reactor, which may increase costs, not only due to the necessary laboratory analyses, but also due to the personnel that has to perform this

task. With a pilot bioreactor this is usually not a problem, since these are routine analyses, but in the field this may not be possible.

An automatic acclimation strategy in principle could be programmed using the dissolved oxygen (DO) concentration as measured variable, since its dynamics may be described by (Spanjers *et al.*, 1996)

$$\frac{\mathrm{d}y}{\mathrm{d}t} = (y_{\mathrm{in}} - y)D_{\mathrm{in}} + (y_{\mathrm{sat}} - y)k_L a - r, \qquad (1)$$

where $y(t)$ is the DO concentration inside the reactor (assumed equal throughout the mixed liquor), y_{in} is the DO concentration in the influent (usually zero), y_{sat} is the dissolved oxygen saturation constant, and $D_{\mathrm{in}}(t) = V(t)/Q_{\mathrm{in}}(t)$ is the dilution rate, with V the current volume and Q_{in} the inflow rate. On the other hand $k_L a$ is the oxygen mass transfer coefficient, which depends (usually nonlinearly) on the airflow rate $Q_{\mathrm{air}}(t)$ and the physicochemical properties of the diffusers and mixed liquor. In a batch reactor, during the reaction phase the above equation simplifies to

$$\frac{\mathrm{d}y}{\mathrm{d}t} = (y_{\mathrm{sat}} - y)k_L a - r, \qquad y(0) = y_0, \qquad (2)$$

with y_0 the DO concentration in the reactor immediately after filling. What makes it possible to use dissolved oxygen as monitoring variable is the fact that the respiration rate $r(t)$ in the above equation can be decomposed in two parts: one proportional to the biomass growth rate and thus to the substrate degradation rate $\mu X(t)$ and another one consisting of the endogenous respiration rate $bX(t)$, which is almost constant, since biomass concentration $X(t)$ has slow dynamics in one SBR cycle (Olsson *et al.*, 2005)

$$r = \frac{1}{Y_O}\mu X + bX \qquad (3)$$

It is then clear that if some parameters are known, the dissolved oxygen dynamics may somehow give an indication of the respiration rate and thus of the biomass activity upon degrading the substrate. Therefore, this information may be used to determine when to stop the reaction. Recall that in a batch reactor, the degradation rate μX depends on the substrate concentration, tending to zero when substrate is depleted.

Assume first that the airflow rate Q_{air} is constant during the reaction and therefore $k_L a$ also remains constant. After complete biodegradation it happens that $r = bX$, which is constant and usually small. Therefore, dissolved oxygen will exponentially reach a steady state $y_{\mathrm{ss}} = y_{\mathrm{sat}} - bX/k_L a$ with rate $k_L a$. To detect the end of the reaction one needs only to observe such an exponential behavior on the signal $y(t)$. This is indeed possible when the biomass is already acclimated, since μX is significantly larger than bX during biodegradation. This implies that it dominates during the reaction and thus the DO concentration curve reaches significantly low values for a sufficient airflow rate, from which its exponential convergence to y_{ss} may be observed. This in fact has been used in a so-called *variable time control* strategy to enhance biodegradation capacities in a SBR treating synthetic wastewater with high concentrations of 4-chlorophenol (Buitrón *et al.*, 2005). However, during the first cycles of acclimation, this strategy is not applicable, mainly because the metabolic respiration rate μX is rather small compared to endogenous respiration. This is clearly illustrated in a figure by Moreno-Andrade and Buitrón (2004), where a constant airflow of 1.5 L/min was used during the whole acclimation period. To implement such a control strategy an operator should know in advance which value of Q_{air} to set in order to observe such a behavior of the DO signal without compromising the degradation because of limiting dissolved oxygen conditions.

The previous discussion motivates the need for a better automatic control strategy for acclimation. The present study proposes such a strategy, which first implements a controller to regulate dissolved oxygen at a suitable setpoint by manipulating the airflow rate, and then uses the manipulated variable in an algorithm to detect mineralization.

Implementing a dissolved oxygen controller is not an easy task for batch systems, because the degradation rate is not nearly constant, as in continuous systems. There are several control strategies that have been proposed for activated sludge systems, that range from simple PID controllers to adaptive or model predictive schemes (Olsson *et al.*, 2005; Lindberg and Carlsson, 1996; Chotkowski *et al.*, 2005), but these may not be applicable to batch systems, as previously discussed. The controller proposed here is an I/O linearizing scheme using Q_{air} as input and DO concentration as output, coupled with a PID controller with anti-windup.

In the next section, the materials and methods used are explained, including the experimental bioreactor setup, the analyses performed, the DO controller, and the automatic end-of-reaction detection algorithm. Following this, in the next section results are presented and discussed, and finally some conclusions are given.

2. MATERIALS AND METHODS

2.1 Sequencing batch reactor

The bioreactor consisted of a jacketed 10 L cylindrical tank with a conical bottom, with a minimal volume of $V_{\mathrm{min}} = 3$ L, an operating volume of

$V_{\max}$ = 7 L. It was equipped with a mixer to guarantee homogeneity of the mixed liquor in the reactor. It operated allowing 5 minutes to fill at a rate of Q_{in} = 16 L/h, a variable reaction time that lasted until almost complete biodegradation of substrate, a settling time of 30 min, and an idle time of only 5 min. During fill and react, air was diffused through a ceramic diffuser at the bottom of the reactor and controlled using a mass flowmeter/controller (Aalborg model GFC17), whose setpoint was externally set and limited to a maximum of 3.5 L/min. Digital and externally controllable persitaltic pumps were used to fill and draw (MasterFlex 7523-20). Temperature was controlled at 20 ± 1º by recirculating water through the reactor jacket using an immersion circulator (Cole-Parmer). Synthetic wastewater with a concentration of 110 mg/L of 4-chlorophenol (4CP) as model compound, complemented with nutrients according to the Association Française de Normalisation (AFNOR) (1985) was used as influent. A photograph of the bioreactor system is shown on figure 1.

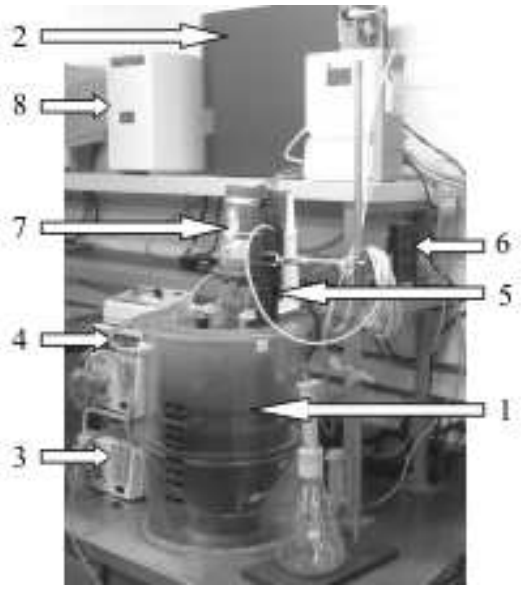

Fig. 1. Experimental setup of the pilot SBR: bioreactor (1), personal computer (2), fill pump (3), draw pump (4), DO sensor (5), mass flow controller (6), mixer (7), UPS (8).

2.2 Hardware and analytical methods

Dissolved oxygen was measured using an industrial polarographic sensor and transmitter (Endress-Hauser model COS41 and Liquisys-S COM223). The measured and command signals were read and written using two data acquisition cards (National Instruments PCI6025E and USB6009) mounted on a personal computer, on which software programmed using the LabView package (National Instruments) was used to control the whole process. The self-developed software package, named BioReC (BioReactor Control), was used to implement the control algorithms.

Substrate concentration was measured taking samples and processing them offline using the colorimetric technique of 4-aminoantipyrine and total and volatile suspended solids (TSS and VSS) analyses were determined according to the Standard Methods (APHA & AWWA & WPCF, 1992). These analyses were performed to evaluate 4CP mineralization and reactor operating parameters. The metabolite (5-chloro-2hydroxy-muconic acid semialdehyde) formed by an alternate degradation route of 4CP by the microorganisms, which can be inhibitory for the microorganisms, was also determined by spectrophotometry at 380 nm using a HACH spectrophotometer.

2.3 Dissolved oxygen control

The PID controller is perhaps the most widely used in process control due to its reliability and simplicity (Ang *et al.*, 2005). Its design is straightforward and does not necessarily require a model of the process. The control signal $u(t)$, which in this case is $u = Q_{\text{air}}$, is calculated using the expression

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(s)\mathrm{d}s + T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right) \quad (4)$$

where $e(t) = y_{\text{ref}}(t) - y(t)$, with y the output of the system and y_{ref} the reference output or setpoint. The PID controller parameters K_p, T_i and T_d need tuning, which can be done manually or using specialized software (Ang *et al.*, 2005).

Two problems arise during its practical implementation. The first one is the derivative term $\mathrm{d}e/\mathrm{d}t$, which cannot be implemented exactly. However, since the signals are discretized and ultimately processed in a computer, the derivative can be computed with a differentiator followed by a median filter to eliminate some of the unavoidable noise amplification.

The second problem is actuator saturation. The airflow is limited to be between 0 and $Q_{\text{air}}^{\max}$. If the controller demands the actuator to operate beyond its limits, the integrator may suffer from windup. A standard anti-windup technique can be implemented using a feedback signal of the difference between the theoretical input $u(t)$ and the actual control signal capped by the actuator limits $\bar{u}(t)$ as follows:

$$u(t) = K_p \left(e(t) + T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} + \right.$$
$$\left. + \frac{1}{T_i} \int_0^t \left(e(s) + \frac{u(s) - \bar{u}(s)}{\gamma K_p} \right) \mathrm{d}s \right). \quad (5)$$

The design parameter γ is used for tuning and a value between 0.1 and 1 is usually enough.

Since a PID controller may not be adequate because of the large variations in the respiration rate $r(t)$, the proposed controller incorporates a linearizing feedforward part. The model considered is that of equation (1), plus the algebraic nonlinear relationship between $u = Q_{\mathrm{air}}$ and $k_L a$

$$k_L a(Q_{\mathrm{air}}) = \frac{(m+1) k_L^* a Q_{\mathrm{air}}}{Q_{\mathrm{air}}^{\max} + m Q_{\mathrm{air}}}, \quad (6)$$

where $k_L^* a$ is the value of $k_L a$ when $Q_{\mathrm{air}} = Q_{\mathrm{air}}^{\max}$ and m is a parameter that determines the nonlinearity of the relation.

Assume that the respiration rate $r(t)$ is measured. Then it is possible to exactly linearize the system. Set as desired model reference the system

$$\frac{\mathrm{d}y_d}{\mathrm{d}t} = \frac{1}{\tau_d} \left(y_{\mathrm{ref}} - y_d \right), \quad (7)$$

with τ_d some desired time constant (a design parameter) and equate both right hand sides of (1) and (7) to solve for $k_L a$, *i.e.*

$$k_L a = \frac{\left(y_{\mathrm{ref}} - y \right) / \tau_d + D_{\mathrm{in}} y + r}{y_{\mathrm{sat}} - y}. \quad (8)$$

The input to the system, *i.e.* the airflow Q_{air}, is computed by solving (6), such that

$$Q_{\mathrm{air}} = \frac{k_L a Q_{\mathrm{air}}^{\max}}{k_L^* a + m \left(k_L^* a - k_L a \right)}. \quad (9)$$

Because the respiration rate $r(t)$ cannot be measured on-line, it must be approximated. This is done using the measured DO and an approximation of its time derivative using (1):

$$\hat{r} = \left(y_{\mathrm{sat}} - y \right) k_L a - D_{\mathrm{in}} y - \widehat{\dot{y}}, \quad (10)$$

where $\widehat{\dot{y}}$ is the estimated time derivative of DO, calculated using a differentiator and a median filter. Furthermore, $\hat{r}$ is truly implemented as the outcome of (10) after a linear lowpass filter. This estimator, together with (8) and (9) constitute an implementable linearizing controller. However, it is still prone to plant-model mismatches and time delays due to the estimators. Therefore, for better performance, the previous PID controller with anti-windup was implemented as an outer loop in a cascade control, such that the airflow Q_{air} was computed using (5), adding the linearizing term of (9), computed using (8) and (10).

2.4 Automation of the acclimation phase

Once dissolved oxygen could be regulated at a setpoint y_{ref}, the acclimation phase can be automated. The idea behind the proposed algorithm for this task is simple. It is schematized in figure 2. The operator decides the duration of a timer and

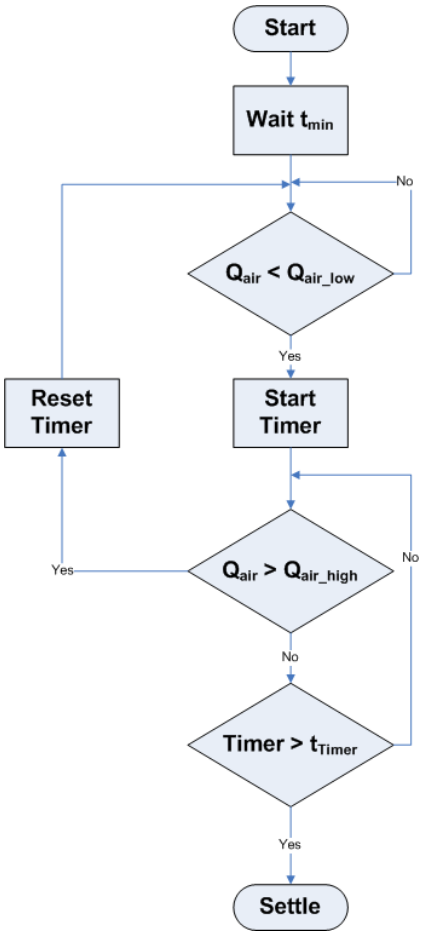

Fig. 2. Flow diagram for the automatic detection of the reaction phase.

two threshold values: $Q_{\mathrm{air}}^{\mathrm{low}}$ and $Q_{\mathrm{air}}^{\mathrm{high}}$. After some initial time to wait for the dissolved oxygen concentration to reach some quasi-steady state, the algorithm waits until the airflow is below $Q_{\mathrm{air}}^{\mathrm{low}}$; this may be an indicator that the microorganisms are only performing endogenous respiration, thereby needing little oxygen. A timer then starts. If, before the timer ends, the airflow rate goes above the $Q_{\mathrm{air}}^{\mathrm{high}}$ threshold, it means that it was a false alarm and thus the algorithm must wait until Q_{air} goes below $Q_{\mathrm{air}}^{\mathrm{low}}$ again. On the other hand, if the timer ends and Q_{air} remains below $Q_{\mathrm{air}}^{\mathrm{low}}$, this indicates that the reaction must end; so it does.

Such an algorithm is very simple to program, but it necessarily requires a good DO controller. Otherwise, if a prolonged overshoot occurs, the airflow may remain below the low threshold value waiting for the microorganisms to naturally consume enough oxygen to reach the setpoint, thus ending the reaction phase prematurely.

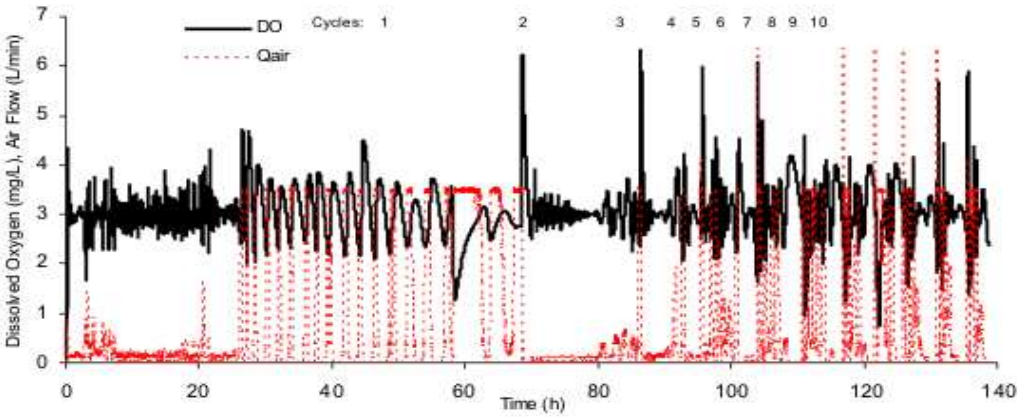

Fig. 3. First ten cycles during acclimation to 4CP biodegradation.

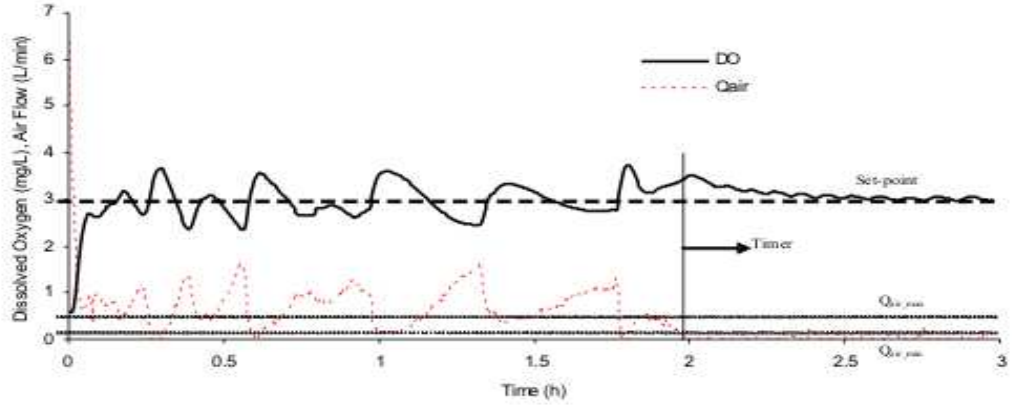

Fig. 4. Close-up of the seventh cycle during acclimation to 4CP biodegradation.

3. RESULTS AND DISCUSSION

3.1 Automatic acclimation strategy

The bioreactor was inoculated with sludge from a nearby municipal activated sludge treatment plant. Synthetic wastewater with a concentration of 110 mg/L of 4CP as carbon source was used as influent. Automatic acclimation using the proposed strategy was started and during the first (slow) reaction the controller had to be tuned manually. The DO setpoint was set at 3 mg/L. The 4CP concentration was monitored to corroborate its biodegradation. The next cycles the automatic acclimation strategy took control of the reactor operation. In figure 3 the behavior of dissolved oxygen and airflow during the first ten cycles is shown. It is interesting to notice how, during the first cycle and due to incorrect tuning of the DO controller, there are many oscillations in the DO signal. It becomes better for the next cycles, but there are still some oscillations. However, the controller is able to keep the DO concentration close to the setpoint, and most importantly, it is able to detect the end of the reaction correctly. A close-up of the seventh cycle is shown on figure 4, where the controller performance is more evident. The mean DO concentration during the reaction phases of the first eleven cycles was 3.046 ± 0.125 mg/L, which confirms adequate performance of the controller.

Regarding the acclimation, the reaction time was reduced from 68.8 h on the first cycle to 26.7 h the second cycle, and gradually reduced to only 3.217 h on the eleventh cycle, when biomass was assumed to be completely acclimated. The specific degradation rate was incremented from 0.519 mgCOD/gVSS-h on the first cycle to 18.28 mgCOD/gVSS-h on the eleventh. Biomass concentration started at 2.9 gVSS/L during the first cycle, then some of it was washed out during the second cycle, reaching 1.82 gVSS/L, but it then recovered up to 2.01 gVSS/L for the tenth cycle. Afterwards it was maintained around this value by purging some biomass periodically. Despite the increasing process load, sludge had with very good settling properties.

3.2 Long-term operation

After acclimation the automatic end-of-reaction detection algorithm was tested for long-term operation of the reactor. The DO controller was tuned periodically, but only minor modifications were made on its parameters. A typical curve is shown on figure 5, together with a measured kinetic curve of 4CP biodegradation. Notice that as soon as the substrate has been consumed the airflow rate needed is minimal.

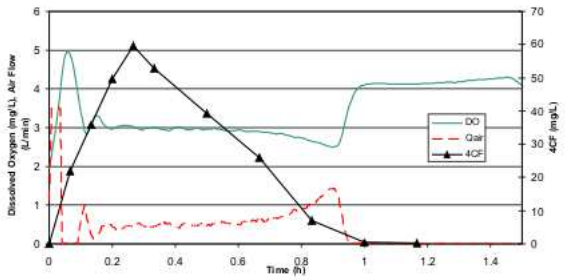

Fig. 5. Typical dissolved oxygen behavior and substrate kinetics with the DO controller.

For this particular cycle, the setpoint was 3 mg/L and the controller was able to maintain an average of 3.05 ± 0.48 mg/L. Preliminary studies showed that such a setpoint was optimal, not compromising biodegradation. Lower setpoints seemed to favor an alternate degradation route that produced a toxic inhibitory metabolite. The mean airflow was 0.66 ± 0.62 L/min, and the volume of air supplied was 39.55 L in 57 min of reaction time. A strategy that maintains a constant airflow of 1.5 L/min would yield a supplied air volume of 85.5 L for the same 57 min. There is thus a 53.7% reduction in supplied air volume by using dissolved oxygen control, which might translate into substantially less energy consumption by aerators when scaling this process. The results are even more dramatic if one considers the whole cycle including the time needed to finally end the reaction phase.

4. CONCLUSIONS

A strategy for automatic acclamation of biomass to biodegrade toxic compounds has been proposed. The experimental results show that such a strategy is indeed a viable alternative, showing stable operation of the reactor after acclimation and good performance of the DO controller. Further studies will focus on enhancing the controller.

5. ACKNOWLEDGEMENTS

This project was funded by DGAPA-UNAM project IN104805. Jaime Pérez-Trevilla is thanked for his help during the experimental part of this work.

REFERENCES

Ang, K.H., G. Chong and Y. Li (2005). PID control system analysis, design, and technology. *IEEE Trans. Control Syst. Tech.* **13**(4), 559–576.

APHA & AWWA & WPCF (1992). *Standard Methods for the Examination of Water and Wastewater*. American Public Health Organization. New York.

Association Française de Normalisation (AFNOR), (1985). *Evaluation en milieu aqueux de la biodégradabilité aérobie "ultime" des produits organiques solubles. Méthode par analyse du carbone organique dissous (COD)*. Norme Française NF T 90–312. Paris.

Buitrón, G., M.-E. Schoeb, I. Moreno-Andrade and J. Moreno (2005). Evaluation of two control strategies for a sequencing batch reactor degrading high concnetration peaks of 4-chlorophenol. *Water Research* **39**, 1015–1024.

Chotkowski, W., M.A. Brdys and K. Konarczak (2005). Dissolved oxygen control for activated sludge processes. *Int. J. Syst. Sci.* **36**(12), 727–736.

Lindberg, C.-F. and B. Carlsson (1996). Nonlinear and setpoint control of the dissolved oxygen concentration in an activated sludge process. *Wat. Sci. Tech.* **34**(3-4), 135–142.

Moreno-Andrade, I. and G. Buitrón (2004). Variation of the microbial activity during the acclimation phase of a SBR system degrading 4-chlorophenol. *Wat. Sci. Tech.* **50**(10), 251–258.

Moreno, G. and G Buitrón (2004). Influence of the origin of the inuculum and the acclimatization strategy on the degradation of 4-chlorophenol. *Bioresource Technology* **94**(2), 215–218.

Olsson, G., M.K. Nielsen, Z. Yuan, A. Lynggaard-Jensen and J.-P. Steyer (2005). *Instrumentation, Control and Automation in Wastewater Systems*. Vol. 15 of *Scientific and Technical Reports*. IWA Publishing. London.

Spanjers, H., P. Vanrolleghem, G. Olsson and P. Dold (1996). Respirometry in control of activated sludge processes. *Wat. Sci. Tech.* **34**, 117–126.

Wiggings, B.A., S.H. Jones and M.A. Alexander (1987). Explanations for the acclimation period preceding the mineralization of organic chemicals in aquatic environments. *Appl. Environ. Microbiol.* **53**, 791–796.

Wilderer, P.A., R.L. Irvine and M.C. Goronszy (2001). *Sequencing Batch Reactor Technology*. Vol. 10 of *Scientific and Technical Reports*. IWA Publishing. London.