Improving the start-up of an EBPR system using OUR to control the aerobic phase length: a simulation study

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Abstract The enhanced biological phosphorus removal (EBPR) process is based on enriching the sludge with polyphosphate accumulating organisms (PAO) which are scarce in conventional non-EBPR wastewater treatment plant sludge. Hence, the start-up of EBPR systems (i.e. enriching the sludge with PAO) can be very slow and complex. A simulation study of a possible improvement of the start-up of an EBPR system in a sequencing batch reactor is presented in this work. The improvement is based on reducing the length of the aerobic phase so that it coincides with the depletion of orthophosphate from the medium. This improvement, though verified by simulation to be very successful, requires a good on-line orthophosphate sensor. To avoid this technical limitation, a link between oxygen uptake rate (OUR) measurements and orthophosphate presence is proposed. This link allows the control of the aerobic phase length with OUR as a measured variable and, consequently, a considerable improvement with respect to the conventional fixed aerobic phase length operation. An improvement of 95% in the ratio of PAO to heterotrophs and an increase of 30% in the final amount of PAO in sludge is achieved with this control strategy. The kinetic mod for simulations was a modification of the Activated Sludge Model 2d.

Keywords Activated sludge models; control; enhanced biological phosphorus removal; oxygen uptake rate; polyphosphate accumulating organisms; sequencing batch reactor

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Introduction

Enhanced biological phosphorus removal (EBPR) is widely accepted as one of the most economical and sustainable processes to remove phosphorus from wastewater, but at the same time, it is a complex process when compared to biological removal of organic matter (COD) or nitrogen. The EBPR process is based on the enrichment of activated sludge with polyphosphate accumulating organisms (PAO). Under anaerobic conditions, PAO take up organic substrates (preferably volatile fatty acids) and store them as poly-hydroxyalkanoates (PHA), while the degradation of intracellular glycogen provides reducing equivalents (Mino *et al.*, 1987; Smolders *et al.*, 1995). The energy for this process is partly obtained from the glycogen degradation but mostly from the hydrolysis of the intracellular stored polyphosphate (polyP), resulting in an orthophosphate (S_P) release into solution. In the subsequent aerobic phase, PAO take up excessive amounts of S_P to recover the intracellular polyP levels by oxidising the stored PHA. Meanwhile they grow and replenish the glycogen pools using PHA as both carbon and energy sources (Smolders *et al.*, 1995). Net phosphorus removal is achieved by wasting sludge after the aerobic period when the biomass contains high levels of polyP.

In some of the exiting EBPR systems, the aerobic phase is longer than the time required by PAO to uptake S_P from the medium. From the depletion of S_P until the end of the aerobic phase, PAO are not favoured in front of other organisms present in the biomass, such as ordinary heterotrophic organisms (OHO) and/or glycogen accumulating organisms (GAO). Hence, the rest of the aerobic phase may not be necessary (it could

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even be detrimental) for PAO growth (Brdjanovic *et al.*, 1998). The main purpose of this study was to test by simulation a possible improvement in the start-up of an EBPR system operating in a sequencing batch reactor (SBR). The operational modification included consisted of controlling the length of the aerobic phase by avoiding periods with no S_P in the medium. Dassanayake and Irvine (2001) pointed out that avoiding periods without S_P could be beneficial for enriching the sludge with PAO and designed a system with shorter aerobic phase but without length control as proposed in this work. Linking the aerobic phase length to S_P presence was tested to be successful, but difficult and expensive to implement in real EBPR systems since it required an on-line S_P measurement. However, this study showed that oxygen uptake rate (OUR) value could also be linked to the S_P concentration and, then, the control on the aerobic phase length could be developed using OUR as the measured variable.

Thirty days of SBR start-up were simulated using a model which included all the SBR phases. The biological model to describe the biological reactions occurring in the anaerobic and aerobic phases was a modification of the Activated Sludge Model 2d (ASM2d) (Henze *et al.*, 2000) including glycogen economy (Guisasola *et al.*, 2004). Different control strategies were tested using S_P and OUR as the measured output and the final values of the main compounds after 30 days of simulation were compared with the conventional EBPR system (fixed aerobic phase length).

Materials and methods

SBR model development

The model for the whole SBR cycle simulation could be divided in five sequential phases: feed, anaerobic, aerobic, settling and extraction. Biological reactions were only considered in the anaerobic and in the aerobic phases.

1. *Feed phase:* This phase was simulated as an instantaneous process using mass balances. The influent flow was 5 L and contained COD (as acetate) and P and enough essential micronutrients for microbial growth so that no limitations occurred in the reactor.
2. *Anaerobic phase:* This phase was characterised by a constant length of 2 h and an oxygen setpoint of zero mg O_2/L.
3. *Aerobic phase:* The oxygen set point value in this phase was set to 8 mg O_2/L to avoid any oxygen limitation. The length of this phase could be constant (3 h) or variable depending whether there was control or not.
4. *Settling and extraction phases:* These two phases lasted 1 h in total and were considered together for model simplification. The concentrations of the state variables at the end of the cycle were calculated with mass balances according to the waste and the total volume extracted (5 L).

Biological model

The model used for the description of the biological processes was a modification of the ASM2d. This modification consisted of omitting autotrophic and physical precipitation processes and including glycogen economy in the PAO processes. The contemplation of the glycogen as an important compound implied the inclusion of the glycogen aerobic restoration process and some stoichiometric modifications as detailed in Guisasola *et al.* (2004). The model stoichiometry and kinetics are shown in Table 1. The default parameters of ASM2d were used except for the parameters related with glycogen which were taken from Pijuan *et al.* (2004) (Table 2). The OHO population was included in the biological model, since the competition between OHO and PAO had a strong influence on PAO dynamic behaviour. Moreover, if an

Table 1 Model stoichiometry and kinetics[a]

	Process	Stoichiometry										Kinetics
		$b > S_A$	S_F	S_{PO4}	S_O	X_{PHA}	X_{GLY}	X_{PAO}	X_H	X_S	X_I	X_{PP}	
1	Aerobic hydrolysis		$(1 - f_{SI})$	ν_{1P}						-1			$k_H \times (X_S/X_H)/(K_X + X_S/X_H) \times M_O \times X_H$
2	Anaerobic hydrolysis		$(1 - f_{SI})$	ν_{2P}						-1			$k_H \times \eta_{FE} \times (X_S/X_H)/(K_X + X_S/X_H) \times K_O/(K_O + S_O) \times X_H$
3	X_{PHA} storage	$-Y_{AC3}$		Y_{PO}		1	Y_{GLY3}					$-Y_{PO}$	$q_{PHA} \times M_A \times (X_{PP}/X_{PAO})/(K_{PP} + X_{PP}/X_{PAO}) \times (X_{GLY}/X_{PAO})/(K_{GLY} + X_{GLY}/X_{PAO}) \times X_{PAO}$
4	X_{PP} storage			-1	$-Y_{PHA}$	$-Y_{PHA}$						1	$q_{PP} \times (X_{PP}/X_{PAO})/(K_{PP} + X_{PP}/X_{PAO}) \times (K_{MAX} - X_{PP}/X_{PAO})/(K_{IPP} + K_{MAX}X_{PP}/X_{PAO}) \times M_O \times M_P \times X_{PAO}$
5	X_{GLY} storage				$-(1 - Y_{GLY5})$	-1	Y_{GLY5}						$q_{GLY} \times (X_{GLYMAX} \times X_{GLY}/X_{PAO}) \times (X_{PHA}/X_{PAO})/(K_{PHA} + X_{PHA}/X_{PAO}) \times M_O \times X_{PAO}$
6	X_{PAO} growth			$-i_{BPM}$	$1 - 1/Y_{PAO}$	$-1/Y_{PAO}$		1					$\mu_{PAO} \times M_P \times (X_{PHA}/X_{PAO})/(K_{PHA} + X_{PHA}/X_{PHO}) \times M_O \times X_{PAO}$
7	X_{PAO} lysis			ν_{7P}				-1		$(1 - f_{XI})$	f_{XI}		$b_{PAO} \times X_{PAO}$
8	X_{PP} lysis			1								-1	$b_{PP} \times X_{PP}$
9	X_{PHA} lysis	1				-1							$b_{PHA} \times X_{PHA}$
10	X_{GLY} lysis		1				-1						$b_{GLY} \times X_{GLY}$
11	X_H growth on S_A	$-1/Y_H$			$1 - 1/Y_H$				1				$\mu_H \times M_O \times M_A \times M_P \times S_A/(S_F + S_A) \times X_H$
12	X_H growth on S_F		$-1/Y_H$		$1 - 1/Y_H$				1				$\mu_H \times M_O \times M_F \times M_P \times S_F/(S_F + S_A) \times X_H$
13	X_H lysis								-1	$(1 - f_{XI})$	f_{XI}		$b_H \times X_H$
14	Fermentation	1	-1										$q_{FE} \times K_O/(K_O + S_O) \times K_F/(K_F + S_F) \times X_H$

[a]MI, Monod limitation kinetics: $M_I = S_I/(K_I + S_I)$

Table 2 Model parameters

Parameter	Description	Value	Parameter	Description	Value	Parameter	Description	Value
k_H (1/d)	Hydrolysis maximum rate	3	K_P (mg P/L)	S_P semisaturation (growths)	0.01	Y_{GLY3}	X_{GLY} degraded/X_{PHA} stored	0.42
K_X (gX_S/gX_H)	Hydrolysis semisaturation	0.1	b_{PP} (1/d)	X_{PP} lysis constant	0.1	K_{MAX} (gX_{PP}/gX_{PAO})	Maximum X_{PP}/X_{PAO} ratio	0.34
f_{XI}	Lysis Inert fraction	0.1	b_{GLY} (1/d)	X_{GLY} lysis constant	0.1	K_{IPP} (gX_{PP}/gX_{PAO})	X_{PP} storage inhibition	0.02
q_{PHA} (gX_{PHA}/gX_{PAO}/d)	X_{PHA} maximum storage rate	5.76	ν_{7PO}	Biomass P release in lysis	0.01	q_{GLY} (1/d)	X_{GLY} production rate	22
K_{PP} (gX_{PP}/gX_{PAO})	X_{PP} semisaturation	0.01	Y_H	X_H growth yield	0.7	Y_{GLY5}	X_{GLY} produced/X_{PHA} degraded	1
Y_{PO} (g P/gCOD)	S_P release/S_A uptake	0.55	i_{BPM} (gP/gX)	P content biomass	0.02	Y_{PAO}	X_{PAO} growth yield	0.625
K_{GLY}	X_{GLY} semisaturation	0.001	K_F (mg COD/L)	S_F semisaturation	4	b_{PAO} (1/d)	X_{PAO} lysis constant	0.1
q_{PP} (gX_{PP}/gX_{PAO}/d)	X_{PP} maximum storage rate	4.07	η_{FE}	Anaerobic reduction factor	0.4	b_{PHA} (1/d)	X_{PHA} lysis constant	0.1
K_{PS} (mg P/L)	S_P semisaturat. X_{PP} storage	0.02	ν_{1PO}, ν_{2PO}	Hydrolysis P release	0	b_H (1/d)	X_H lysis constant	0.1
K_{PHA} (mg COD/L)	X_{PHA} semisaturation	0.07	Y_{PHA} (g COD/g P)	X_{PHA} degraded/S_P accumulated	0.2	f_{SI}	Hydrolysis S_I production	0
X_{GLYMAX}	Maximum X_{GLY}/X_{PAO} ratio	0.28	Y_{AC3}	S_A uptaken/X_{PHA} stored	0.82	μ_H (1/d)	X_H maximum growth rate	6
μ_{PAO} (1/d)	X_{PAO} maximum growth rate	1	K_S (mg COD/L)	S_A semisaturation	4	q_{FE} (g S_F/g X_H/d)	Fermentation maximum rate	3

EBPR system was started with typical wastewater treatment plant (WWTP) biomass, the ratio of PAO to OHO in biomass would be very low, and the OHO behaviour would be significant in the first days of operation.

Simulation tools

The modelling software used was MATLAB 6.5. The differential equations were solved using the function *ode15s*, which is particularly indicated for stiff systems.

Results and discussion

One cycle simulation

Figure 1 depicts the simulated profiles of the main state variables in a conventional anaerobic and aerobic cycle with fixed aerobic phase length. In the anaerobic phase, acetate (S_A) is taken up and stored in PHA linked to glycogen degradation. The OUR value in this phase is zero. The energy necessary for this process is mostly obtained from polyP hydrolysis which results in S_P release. Finally, neither PAO nor OHO (X_H) grows on this phase and the lysis process cause the decay in both biomasses. On the other hand, under aerobic conditions, PAO uses the previously stored PHA to restore its internal glycogen pools, to uptake S_P from the medium and store it as polyP, to grow and, finally, it is oxidised for maintenance purposes.

The OUR reaches a high value at the start of the aerobic phase. Afterwards, and once the phosphorus is totally depleted, the OUR value drops off. The reason is that the OUR is linked to the polyP storage process (see model stoichiometry on Table 1). PAO growth decreases sharply when the S_P is totally depleted (~200 min). Hence, the time period between S_P depletion and the aerobic phase end becomes a waste of time and energy according to the aim of enriching the SBR population with PAO. The last 100 min could have been removed without any negative effect.

Start-up simulations

The initial values of each simulation are shown in Table 3. All the simulations were run for 30 days. The amount of P and COD in the feed was designed so that it increased proportionally to the PAO fraction in the biomass. Moreover, this feed pattern (Table 4) was chosen so that PAO were favoured against other species (i.e. all the COD and the P should have been taken up in the anaerobic phase and aerobic phase, respectively). A waste of 0.25 L at the end of the aerobic phase was also included from the tenth cycle to describe a real start-up more reliably.

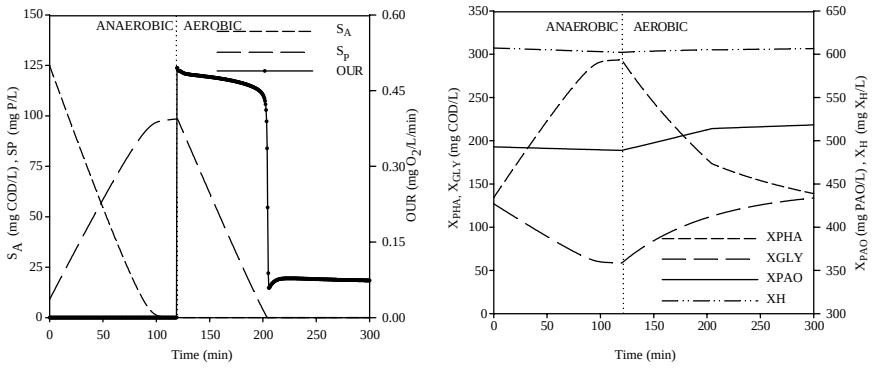

Figure 1 Profiles of the main compounds in a conventional EBPR cycle with fixed aerobic phase

Table 3 Initial values for start-up simulations

Parameter	Initial value	Parameter	Initial value
Biomass (mg VSS/L)	4,000	X_{GLY} (mg COD/L)	30
X_{PAO} (mg PAO/L)	200	X_S (mg COD/L)	0
X_H (mg COD/L)	1,600	X_{PP} (mg P/L)	20
X_{PHA} (mg COD/L)	10	X_I (mg COD/L)	0

Table 4 Feed pattern

Cycles	1–10	10–20	20–30	30–50	50–75	75–100	100–125	125–150	150–175
mg P/L Feed	6	10	14	18	22	26	30	34	40
Mg COD/L Feed	50	100	200	250	350	400	450	500	550

Cycles with fixed aerobic phase length (no control). Each cycle lasted 6 h, so 120 cycles could be placed in 30 days. The profiles of the main compounds along this simulation without control are depicted in Figure 2. The OHO population decreased along the start-up period because they could only grow on COD under aerobic conditions and the only COD present in the aerobic phase was due to the hydrolysis and fermentation processes, which was a very low COD value. On the contrary, PAO rose considerably, because under aerobic conditions they could grow on the previously stored X_{PHA}. Hence, it was proven that the start-up with fixed aerobic phase length could be successful. However, as will be demonstrated below, it could be optimised and improved with a control on the length of the aerobic phase.

Cycles with variable aerobic phase length (P control). Figure 3 depicts the simulation of the start-up with the length of the aerobic phase controlled using S_P as the measured variable. The control strategy implemented was to stop the aerobic phase and start the

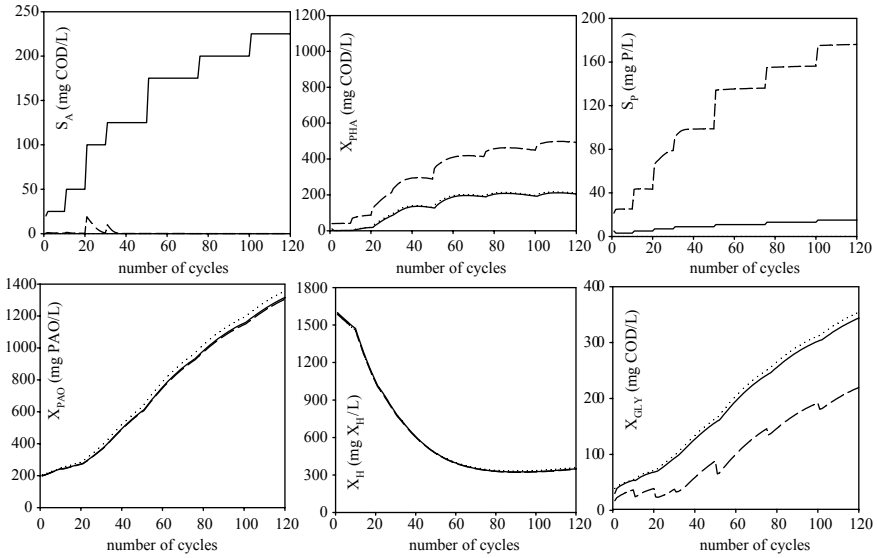

Figure 2 Start-up period without aerobic phase length control (6-h cycle). Anaerobic phase initial (solid), aerobic phase initial (dashed) and aerobic phase end (dash-dotted)

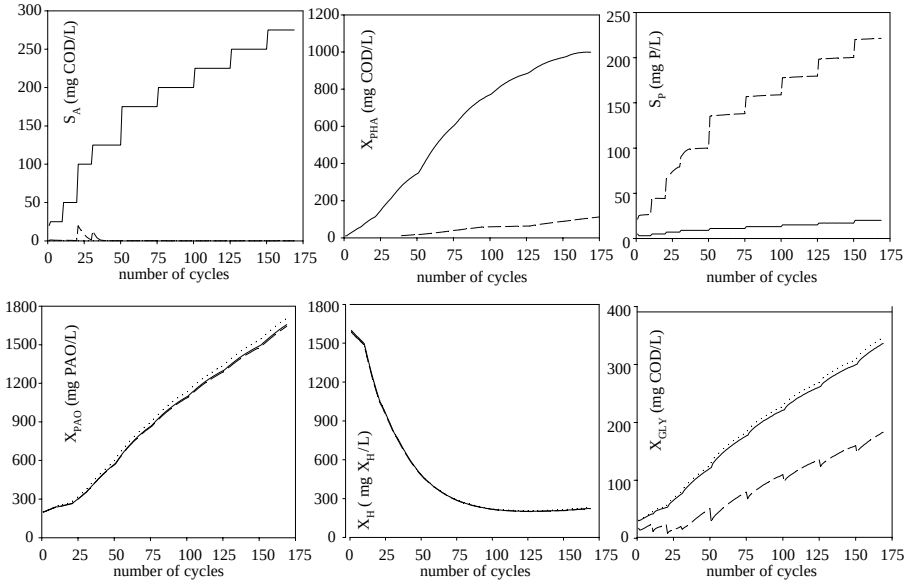

Figure 3 Start-up period with P-control (variable aerobic phase length). Anaerobic phase initial (solid), aerobic phase initial (dashed) and aerobic phase end (dash-dotted)

settling/extraction phases when S_P became lower than 0.1 mg P/L. This control strategy avoided unnecessary PHA oxidation in the absence of S_P and allowed to complete 120 cycles in only 513 h due to the reductions in the aerobic phase length. That meant 207 h less than the simulations without control. Hence, 29% of the start-up time was ineffective for PAO growth and as such it could be omitted. Figure 3 displays the values obtained during 170 cycles. These were the number of cycles that could be placed in 30 days of simulation with the control strategy. Hence, the EBPR system start-up became more efficient since more cycles could be performed with this strategy (in the same period of time) than with fixed aerobic length.

A clear difference between the simulations was observed in the PHA trend, which had lower levels and was more fluctuating in the simulations without control. This is because the PHA is continuously oxidised for maintenance purposes during the aerobic phase, which was reduced in the simulations with control. The increase in the PHA levels is a positive secondary effect, of this control strategy because the amount of PHA present at the end of the anaerobic phase governs the extent of P uptake in the subsequent aerobic period.

The value of X_H in both cases seemed to reach a steady-state value. This fact is quite significant, since it showed that a certain fraction of OHO was always present in bio-P sludge. It grew on the COD present in the aerobic phase because of the lysis and hydrolysis processes. Moreover, as can be seen in Table 5, this new control strategy improved the start-up of an EBPR system to a great extend, since the ratio of X_{PAO}/X_H was increased more than 90% and the final amount of X_{PAO} was increased almost 30%. However, this control strategy based on S_P depletion required an accurate on-line S_P sensor for its implementation. In case it was not available, an alternative was proposed which linked an easily measurable variable as OUR to the S_P presence.

Cycles with variable aerobic phase length (OUR and dOUR control). OUR is a widely used output variable for modelling purposes because it is relatively easy to measure

Table 5 Values of the state variables after 30 days of simulation

Cycles placed	No control			P control			OUR control			dOUR control		
Compound/phase	120 cycles			170 cycles			153 cycles			169 cycles		
	SA	SO	EO	SA	SO	EO	SA	SO	EO	SA	SO	EO
SA (mg COD/L)	225	0	0	275	0	0	275	0	0	275	0	0
X_{PHA} (mg COD/L)	205	492	209	998	1,349	1,024	546	897	562	990	1,340	1,015
X_{PAO} (mg X_{PAO}/L)	1,316	1,305	1,356	1,664	1,650	1,714	1,597	1,583	1,647	1,658	1,645	1,708
S_P (mg P/L)	15	176	0	20	221	0	20	219	0	20	221	0
X_{PP} (mg P/L)	274	111	282	515	312	531	404	203	418	512	309	528
X_S (mg COD/L)	6	11	6	13	18	14	9	15	9	13	18	13
X_H (mg X_H/L)	349	347	360	225	223	231	284	282	293	224	222	231
X_{GLY} (mg COD/L)	344	220	354	338	185	347	387	235	399	338	185	348
X_I (mg COD/L)	111	112	114	80	81	82	97	99	100	80	81	82
S_F (mg COD/L)	1	1	2	0	1	1	1	1	3	0	1	1
X_{PAO}/X_H	3.8	3.8	3.8	7.4	7.4	7.4	5.6	5.6	5.6	7.4	7.4	7.4

SA, start anaerobic; SO, start anaerobic; EO, end anaerobic

while it provides a lot of information. Although it has not been commonly used in the literature when dealing with EBPR process, there exists a clear link between EBPR and OUR as can be seen in Table 1 (model stoichiometry) and detailed in Guisasola *et al.* (2004) or Pijuan *et al.* (2005). Figure 4 shows the OUR, OUR first derivative (dOUR) and S_P profiles obtained in the aerobic phase of a conventional EBPR cycle. OUR drops off when S_P is depleted. Then, a possible strategy could be to stop the aerobic phase and start the settling/extraction phases when OUR became lower than a certain value. OUR did not decrease to zero after S_P depletion, but remained in a low constant value because of lysis and hydrolysis processes. The set-point value chosen to test this OUR control strategy was 0.1 mg DO/L/min and the results after 30 days of simulation are shown on Table 5. This OUR control strategy improved the start-up without control, since 153 cycles could be placed in the period of simulation (30 days). However, the improvement is lower than the one observed with the P-control strategy. As an example, the increase of the ratio X_{PAO}/X_H with the OUR control strategy was only 47% when compared to the 90% obtained using the P control strategy.

To improve these values, a new approach using dOUR was planned. When S_P was depleted, a minimum could be observed in the OUR profile. The OUR was always decreasing along the aerobic phase until this minimum was attained. Hence, if the dOUR was calculated, S_P depletion point could be estimated because, the dOUR at this point should move from a negative to a positive value.

This hypothesis was the basis of the last strategy implemented in this work: stop the aerobic phase and start the settling/extraction phases when the first derivative of the OUR became positive.

As shown in Table 5, this strategy was shown to be a very successful since 169 cycles could be placed in 30 days of simulation (only one cycle less than the P-control strategy). The reason for this 'lost' cycle was that OUR values after and before a certain instant of time were needed for a proper estimation of the OUR first derivative in this instant of time. This implied a certain time delay in assessing the minimum of the OUR profile, and consequently, in stopping the aerobic phase. This delay depends on the OUR estimation procedure, particularly on the frequency of OUR sampling. Lower frequency in OUR calculation would imply higher time delays and this last strategy would become less efficient. In this work, a OUR estimation frequency of 10 s is used and then the delay becomes irrelevant since the start-up process is highly improved using an easy measurable output variable such as OUR.

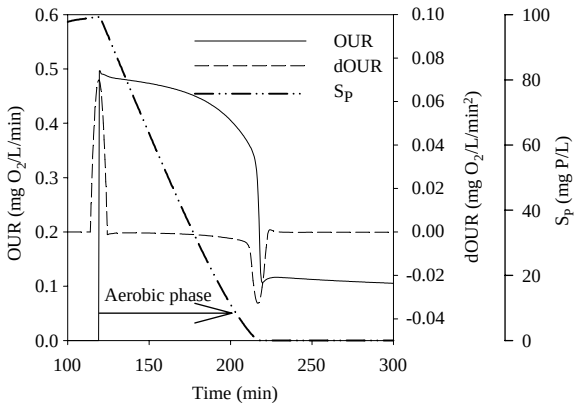

Figure 4 SP, OUR and dOUR profiles in an aerobic phase

Conclusions

- The simulations performed in this work reveal that it is feasible to improve the start-up of an EBPR system in a SBR by reducing the length of the aerobic phase so that it coincides with the total depletion of phosphorus.
- The main improvements observed with the simulations are the increase of the start-up efficiency in terms of PHA internal levels, PAO presence in the final sludge and the achievement of higher phosphorus removal capacity and higher PAO to OHO ratio.
- If an on-line S_P measurement is not available, the OUR can be used as an indicator of S_P presence. Both the absolute OUR value and the OUR first derivative can be used as a measured value in the control strategy.
- The on-line OUR first derivative calculation allows a satisfactory estimation of the S_P depletion point. This was implemented in a control strategy to reduce the aerobic phase length with almost the same results as the ones obtained using S_P as measured variable

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