An alternate oxic-anoxic process automatically controlled.
Theory and practice in a real treatment plant network

P. Battistoni*, R. Boccadoro*, D. Bolzonella** and M. Marinelli*

* Institute of Hydraulics – Engineering Faculty – Marche Polytechnical University, Via Brecce Bianche, 60131 Ancona, Italy (E-mail: idrotre@univpm.it)
** Department of Science and Technology – University of Verona, Strada Le Grazie 15, 37134 Verona, Italy (E-mail: bolzonella@sci.univr.it)

Abstract A simple mathematical model of an alternate oxic-anoxic process has been elaborated. It enables us to optimise the cycle time on the basis of maximum nitrates concentration in the effluent and the desired nitrogen removal performance. At the same time the model can be employed to verify the impact of the variations of flow rate and influent characteristics as well as the operational parameters of the process. Actually, the model confirms the process efficiency but its feasibility in real plants needs a local or remote process control. To verify these theoretical conclusions a real wastewater plant (700 PE) has been upgraded in an alternate oxic-anoxic process. It was implemented with software able to elaborate the data of dissolved oxygen concentration and oxidation reduction potential. Moreover, the evaluation of the flexing points was performed to manage mixer and blowers. A one-year experience of plant management allowed us to obtain very high nitrogen removal. However, the performances were different during wet or dry weather periods. The statistical analysis of probe signals evaluation confirmed the capability of the control device to detect the flexing points during the anoxic phase (70–94%). On the other hand, the capability of detecting the DO signal was lower, in particular when the oxygen demand was similar to the amount of supplied oxygen. The hourly variations of flow rate and mass loading determines different conditions for starting the anoxic phase: over aeration, over loading and the equivalence of oxygen demand and supply, are the main factors determining the blowers stopping.

Keywords Alternate process; dissolved oxygen; oxidation reduction potential; nutrient removal; wastewater treatment

Introduction
A number of small (<10,000 PE) municipal wastewater treatment plants are working in Italy (more than 6,000 plants). In order to achieve the correct process control they require specialised personnel, involving high managing costs. Moreover, the present Italian law standards for nitrogen discharge ($\text{NH}_4$-$\text{N}=11.7 \text{ mg l}^{-1}$, $\text{NO}_3$-$\text{N}=20 \text{ mg l}^{-1}$) can be easily achieved assureing a minimum performance efficiency (average 30%) in nitrogen removal, but it is well known that a low energy cost for the process management can be reached only when the nitrogen removal goes up to 80–90%. As a matter of fact, only a nearly complete recovery of the oxygen bound to nitrogen in nitrates can help the energy saving when used for the oxidation of carbon substrates. Unfortunately, this target is linked both to adequate structures and infrastructures of the treatment plant and to the possibility of a reliable control of the process. In such a way the whole ammonia oxidation and nitrate denitrification can be performed in spite of the daily mass loading fluctuations (during dry weather) and the hydraulic overloading during wet weather events. Generally, an extended aeration or an alternate oxic-anoxic process are adopted: the goal is to obtain the biological nitrogen removal according to a space or a time succession of nitrification (aerobic) and denitrification (anoxic) steps. In the field of the alternate processes the Carousel, the oxidation ditches, the Bio-Denitro, the alternate oxic-anoxic processes and ADJ-Technologies® as an SBR continuously fed are frequently adopted solutions (Araki et al., 1990; Henze et al.; 1998;
Tomlins et al., 2002). The use of the continuously fed alternate process allows an effective nitrogen removal thanks to two different cycles: the first, the aerobic one, achieves the complete ammonia oxidation, whereas the second, the anoxic one, allows the nearly total nitrates denitrification. Moreover, the anoxic phase enables us to achieve low energy consumption because of the oxidation of the organic compounds without oxygen supply. Here, in fact, nitrates instead of oxygen, are the final electron acceptors. The automatic control of the process may be performed according to typical profiles of the dissolved oxygen (DO) and the oxidation-reduction potential (ORP) within the process cycles. Characteristic profiles in the plots of DO and ORP profiles versus time have been mainly observed in the sequential batch reactor (SBR) processes. They are linked to chemical-physical phenomena or biological events and can be successfully used in the process control. In particular, the ammonia breakpoint during the aerobic cycle, identified by a flex-point in the DO profile at the end of ammonia nitrification, and the nitrates breakpoint in the anoxic cycle, identified by a flex-point in the ORP profile at the end of nitrate denitrification process, are the main evident events. The first condition, the ammonia breakpoint, is also observable in the ORP versus time profile, normally in the range 60 – 150 mV. The second condition, the nitrates breakpoint, usually happens in the range –40 – –60 mV (Wareham et al., 1993; Heduit et al., 1996). The last range is higher than the one observed in pre-denitrification/nitrification processes but, according to Deguin (1992) it needs to assure a good performance in nitrates reduction. These suggestions are normally found out in pilot plant studies where constant flow rates and nutrients concentrations in the influent are used. On the other hand, in continuous fed real plants the detection of the flex-points can be difficult because of a lot of factors. Paul et al. (1998) had shown that the mass over- and under-loading, the over- and under-aeration, the nitrification inhibition and the insufficient carbon availability are the main factors involved in hiding of the bending points. In a recent study, according to a preliminary work of calibration where the high and low ORP set points were determined, Zipper et al. (1998) sought the best performances in nitrogen nitrification and denitrification processes with those signals. Moreover, those were used to control the time-length phases. However, the control protocol was considered complex and without reliability when the hydraulic loading changed, both within the day or during wet weather events. An automatic control device, called OGAR, was used to stop the aeration on the basis of the ORP signal; high performances in nitrogen removal were obtained (85–95%) and it was shown that the adopted device was successful when a low loading rate process was performed (Lefevre, 1993; Tomlins et al., 2002). Small municipal wastewater treatment plants adopting the alternate oxic-anoxic process are often automatically controlled (Battistoni et al., 2000, 2003). Here, the blowers are switched on and off by means of timers or of the DO and ORP signal elaboration. This paper will present the theory and the practice of alternate oxic-anoxic process during one year of experimental work on a small wastewater treatment plant to enhance process control and performances. The process has been recently applied in a network of small civil wastewater treatment plants in central Italy to save energy and managing costs.

Methods

The demonstrative plant used in the research originated from the retrofitting of a small municipal wastewater treatment plant (700 PE) without primary sedimentation (Table 1). Only one mixer and the DO and ORP probes were added. The specific volume of the design (200 litres of tank volume per PE) was large enough to perform the alternating cycles process and to operate with sludge retention time (SRT) higher than 20 days. In this way an extended aeration of the activated sludge and a low wasted sludge flow rate were obtained. Characteristics of the wastewater treatment plant are reported in Table 1. Furthermore, the
electromechanical devices previously installed satisfied the requirements for both wastewater pumping and air flow rate, therefore no modifications were necessary. A global specific investment cost of 53 Euros per Person Equivalent was required to upgrade the plant. The investment was mainly intended to introduce some lacking facilities in the treatment plant: a sand and grit removal step, a by-pass, a skimmer mechanism and a sludge recycling pump. The plant was managed by the on-line monitoring of the dissolved oxygen, oxidation reduction potential, pH and temperature values. The chemical-physical characteristics of the treated wastewater and effluent were measured as described in Standard Methods (APHA, 1985).

Results and discussion
Simplified mathematical model
A simplified mathematical model for a continuously fed reactor adopting an alternate oxic-anoxic process can be designed assuming few hypotheses: nitrification and denitrification rates follow a zero order kinetic; nitrates in the plant influent are insignificant; total influent nitrogen can be approximated as ammonia (TKN to NH₄-N ratio in the influent is 1.2); the volumetric loading of influent ammonia is negligible (three times lower) if compared to the oxidative capability of the autotrophs, determined on the basis of a biomass concentration of 3 kg MLSSm⁻³, a specific tank volume of 200 l PE⁻¹ and a nitrification rate of 0.06 kg NH₄-Noxidised kgMLSS⁻¹ d⁻¹. Moreover, the amount of waste activated sludge can be considered negligible because of the extended aeration conditions. On the basis of these assumptions a simplified solution for ammonia and nitrates mass balance during oxic and anoxic phases can be found according to Eqs (1)–(2) and (3)–(4), respectively.

\[
\text{NO}_x \cdot \text{N} = K_n X \cdot t
\]  

\[
\text{NH}_4 \cdot \text{N} = \text{NH}_4 \cdot \text{N}_{t_1} + \frac{\text{NH}_4 \cdot \text{N}_{\text{IN}} \cdot Q}{V} \cdot t - \left(\frac{\text{NH}_4 \cdot \text{N}_{t_1} \cdot Q}{V} + K_n X\right) \cdot t
\]  

\[
\text{NO}_x \cdot \text{N} = \text{NO}_x \cdot \text{N}_{t_0} - \left(\frac{\text{NO}_x \cdot \text{N}_{t_0} \cdot Q}{V} + K_d X\right) \cdot t
\]  

\[
\text{NH}_4 \cdot \text{N} = \frac{Q}{V} \text{NH}_4 \cdot \text{N}_{\text{IN}} \cdot t
\]  

Table 1  Electromechanical characteristics and dimension of the demonstrative plant

<table>
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<th>Design data</th>
<th>m.u.</th>
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<th>Value</th>
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<td>Q</td>
<td>m³hr⁻¹</td>
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<td>Grit chamber</td>
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<td>Drying beds</td>
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<td>Value</td>
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<td>m³</td>
<td>Volume</td>
<td>m³</td>
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</tbody>
</table>
where,

\[ \text{NO}_x-N = \text{Nitrate plus nitrite concentration (mg/l)} \]

\[ \text{NH}_4-N = \text{ammonia concentration (mg/l)} \]

\[ K_n = \text{maximum nitrification constant (d}^{-1}) \]

\[ K_d = \text{maximum denitrification constant (d}^{-1}) \]

\[ Q = \text{influent flow-rate (m}^3\text{d}^{-1}) \]

\[ V = \text{volume of reactor (m}^3) \]

\[ X = \text{mixed liquor suspended solids (mg/l)} \]

\[ t = \text{time (d)} \]

\[ t_c = \text{length of cycle time (d)} \]

subscripts:

IN = influent

\[ t_0 = \text{beginning of anoxic phase} \]

\[ t_1 = \text{beginning of aerobic phase} \]

\[ \text{max} = \text{maximum value} \]

These equations can be used to predict either nitrates and ammonia variations inside the reactor or in the effluent considering a complete stirred reactor. Figure 1 shows the profiles with time of the nitrogen species inside the reactor for a stirred reactor. In the ideal situation the time length of the cycle \( (t_c) \) can be related to kinetic constants and influent characteristics or to the process performances according to Eq. (5).

Furthermore, the model clearly shows that, once \( K_d \) and \( K_n \) are fixed, the time cycle depends on the volume of the reactor and the chemical physical characteristics of the influent while the ammonia and nitrates in the plant effluent are mainly determined by kinetic constants. After \( K_d \) and \( K_n \) are established, the length of time of the anoxic and oxic phases is a function of the incoming mass loading of nitrogen. Finally, the main role of the model is to demonstrate that an extended aeration process can be easily retrofitted to an alternate oxic-anoxic continuously fed reactor. At the same time, the model can be used to forecast the process performance when the values of kinetic constant are modified according to different phenomena as: over aeration, inhibitory effect, lack of carbon substrate and over loading of nitrates in the incoming flow rate during wet weather (Battistoni et al., 2003).

All these elements, related to the variability of the influent characteristic and to
operational conditions of the reactor, clearly show that a time control device should be only partially useful. On the other hand, a successful mode to control the process must be based on elements which explain what really happens inside the reactor: the model mainly confirms that the ORP and DO signals are good tools to control the process since the trend of nitrogen compounds is similar to the one observed in sequencing batch reactors.

Demonstrative small wastewater treatment plant

As a practical application, a real alternate oxic-anoxic cycle wastewater treatment plant (size 700 PE) was provided of a patented device (Battistoni and Chemitec, 1999) to control the end of the nitrification and denitrification steps. Performances were monitored for a one-year experimental period. The main results can be summarized in sixteen homogeneous periods in which the influent temperature ranges from 9 to 23°C while TKN goes up to 60 mg l⁻¹ in the summer season (Table 2). The performances in nitrogen nitrification ($E_n$) ranges from 60 to 91%, they are strongly linked to process temperature, while nitrogen removal is very high: the minimal nitrogen removal for denitrification ($E_d$) Table 2 is obtained during start up and the winter season ($E_d$, 64 – 68% runs 1, 2 and 16 in Table 2) while higher values are always observed in the other runs. A general rule can be observed: $E_d$ is nearly equal to $E_n$, therefore all the nitrified nitrogen is then denitrified. Only during wet weather is $E_d$ higher than $E_n$ since the process is able to remove also nitrates in the influent (up to 12 mgN l⁻¹). Nitrites are never observed after the start up, since they are easily denitrified.

Statistical analysis of DO and ORP

The process is managed on the basis of the elaboration of ORP and DO signals: the detection of bending points in the DO and ORP profiles, enables the automatic device to start and stop blowers and mixers to determine oxic and anoxic phases (Battistoni et al., 2003). The statistical analysis of ORP and DO detections reveals that the determination of the flexing point in the oxygen pattern is more frequent during summer time and wet weather (all runs except run 2, 3). On the other hand, the flexing point of the ORP signal is always revealed with a high percentage of success (range 70–94%). The time length of each cycle phase is

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<th>Date</th>
<th>Run</th>
<th>Influent Temp. °C</th>
<th>Flow, m³ d⁻¹</th>
<th>COD, mg l⁻¹</th>
<th>TKN, mg l⁻¹</th>
<th>$E_n$ %</th>
<th>$E_d$ %</th>
<th>NH₃-N, mg l⁻¹</th>
<th>NO₂⁻-N, mg l⁻¹</th>
<th>NO₃⁻-N, mg l⁻¹</th>
<th>$P_{tot}$, mg l⁻¹</th>
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$E_n$ efficiency in nitrification process, by nitrogen mass balance
$E_d$ efficiency in denitrification process, by nitrogen mass balance
variable according to influent mass loading, however the following general situation can be observed: the time length of the aerobic phase is generally the same except for run 16, and it can be related to a very high oxygen supply (blowers power 7.4 kW). On the other hand, the time length of the anoxic phase gains very high values when the plant must manage a long wet period: in fact, the anoxic phase time goes up to 93 min in run 2.

A detailed analysis of the nitrification and denitrification phases performed during the 0–24 hours/day is done examining 3,447 cycles.

It reveals that several reasons determine the phase ending according to a scenario where incoming mass loading is variable and the blower power is constant. This is a typical situation for small wastewater treatment plants. In particular, for the nitrification process the following cases are evident:

- during night and the early day, when the minimal mass loadings are observed, the time length of the aerobic phase gets a minimal value: nitrification ends mainly for an over aeration phenomenon, and the control device stops the blowers because of the reaching of the maximum DO value. Flexing points were rarely detected (Figure 2);
- during medium and maximum mass loading, the middle day, the flex point determination becomes more easy since oxygen supply and demand are similar. Moreover, the control of the maximum time is active if mass overloading verified (Figure 2);
- the DO flexing point is the main factor influencing the end of the oxic phase in the second part of the day when the mass loading decreases and oxygen supply and demand are similar.

The denitrification phase is always characterized by the appearance of a flex point (80%): this is true also in wet weather conditions if the phase is sufficiently long, while a minimum value of ORP sometimes aids the process. An example of 19 automatically
controlled oxic-anoxic cycles during 24 hours is given in Figure 3. Only for some anoxic phases is it possible to see the bending point because they are not detected by elaboration of the ORP signal.

The theoretical model can be easily employed to foresee the impact of nitrates on the incoming flow rate, of course they determine a higher nitrates concentration at the end of nitrification and a longer denitrification phase. This scenario is presented in Figure 4: its test on experimental results is an indirect confirmation of the process control software feasibility. Figure 5 demonstrates that the denitrification time length increases from 30 to 150 min, according to the nitrate concentration in the influent. Nitrates appear especially in wet weather (6–8 mg/l) for the rural configuration of sewerage territory.

Conclusions

The experimentation of an automatic control device in a demonstrative alternate oxic-anoxic process applied in a small wastewater treatment plant (700 PE) allowed us to draw out some fundamental conclusions.

1. An easy retrofitting of an extended aeration process into an alternate oxic anoxic process, increasing only electromechanical devices, is possible when the wastewater treatment plant has been designed with adequate volume;
2. The mathematical model of the process allows us to determine the optimal time length of oxic-anoxic cycles if rates of nitrification and denitrification processes and the characteristics of the influent wastewater are known;
3. The alternate oxic-anoxic process can be automatically controlled with the elaboration of bending points of DO and/or ORP signals by a patented device;
4. Some critical aspects in process control can be encountered with hydraulic and mass loading variations in dry and wet weather conditions, despite the presence of the automatic control device;

5. A statistical analysis of the oxic and anoxic cycles performed during a given period of time is always recommended to gain information about the efficiency in the process management.

References


