Process using DO and ORP signals for biological nitrification and denitrification : validation of a food-processing industry wastewater treatment plant on boosting with pure oxygen

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Abstract The simultaneous removal of carbonaceous and nitrogenous pollution by the activated sludge process is becoming common in industrial and municipal wastewater treatment plants. An oxygenation monitoring process has been developed, which is based on the dynamic analysis of ORP and DO signals and allows the detection of specific characteristic points at the end of the biological nitrification and denitrification.

The aim of this study is to validate this process in a food-processing industry WWTP (slaughterhouse) having large variations of carbonaceous and nitrogenous loads. In order to treat during the peak period, pure oxygen is used. The first part of the study provides a precise diagnosis of the WWTP operation by the analysis of the ORP and DO signals. It is particularly easy to estimate the level of nitrogen treatment actually achieved and the oxygen requirements, and to detect the over- or under-oxygenated phases.

Thanks to the monitoring process, the aerobic period of each cycle is reduced to the optimal duration, providing a reduction of 30% on the energy consumption compared to a traditional schedule. We have demonstrated that the use of pure oxygen associated with the existing air system is particularly relevant for the peak period. The revamping of an existing plant to simultaneously treat the carbon and the ammonia in the same basin is now technically feasible.

Keywords Activated sludge; denitrification; nitrification; ORP; DO; pure oxygen; control

Introduction

The more stringent directives for nutrient release into the aquatic environment together with the objective of reducing operation costs are leading treatment plant managers to look for simple, cheap and reliable systems for controlling wastewater treatment processes. In France, among the low-loaded activated sludge systems, the Alternating Aerobic-Anoxic Activated Sludge process is the most commonly used for fairly small communities (<50,000 inhabitants). In these plants, it is necessary to manage switching on and off of the aeration but only relatively simple equipment is available. Control methods have been proposed based either on the detection of ORP absolute values (Héduit, 1989; Charpentier *et al*., 1989) or on the relative ORP changes with time (Sasaki *et al*., 1993; Lefevre *et al*., 1993; Caulet *et al*., 1998) or, more recently, on the detection of bending-points on the ORP, oxygen and pH curves (Wareham *et al*., 1993, 1994; Al-Ghusain, 1994; Wouters-Wasiak *et al*., 1994; Hao and Huang, 1996; Plisson-Saune *et al*., 1996; Ra *et al*., 1998; Paul *et al*., 1998).

In the works of these various authors, three bending-points on the ORP curve and one bending point on the DO curve are described. The mechanisms responsible for their appearance are linked to the major biological activities playing a role in a nitrification-denitrification cycle.

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A specific control strategy, named "INFLEX" control has been described by Ferrand *et al.* (1998). It is a control based on bending point detection on both ORP and Dissolved Oxygen (DO) profiles and is backed-up by time-tables and threshold values. The "INFLEX" control showed good efficiency for fitting aeration time to the demand. The more perturbed the system, the more useful the "INFLEX" control.

This system should be tested on different industrial activated sludge treatment plants in order to demonstrate its reliability and robustness and to show how it can save costs or improve treatment efficiency. The objective of the present work is to assess the "INFLEX" control for its ability to adapt the aerated/non-aerated time ratio to the plant load while keeping high treatment performance. The control reliability must be also guaranteed. The effect of using pure oxygen to boost aeration is discussed.

Material and methods

The treatment plant

All the experiments were done on a full scale low-loaded Alternating Aerobic-Anoxic activated sludge wastewater treatment plant fed with a slaughterhouse effluent in the south of France during a period between December and June. The major characteristics of this plant influent are described in Table 1. All the analysis methods were the French Standard Methods (AFNOR, 1994). The reference electrode of ORP probe is Ag/AgCl.

The capacity of the plant was 3,500 p.e. The organic load was around 0.062 kg COD/kg MLSS.d and the average MLSS concentration in the tank was 8.5 g/l (6.7 g/l of VSS). The plant configuration is represented schematically in Figure 1. The influent was first screened and sand and grease were removed by sedimentation and air flotation. A 200 m^3 tank was used as a buffer and the feeding of the aeration tank was performed by two pumps having a pumping capacity of 2 m^3/h. The operation of the second pump depended on the production. Sometimes the buffer was completely empty before weekends. Aeration was

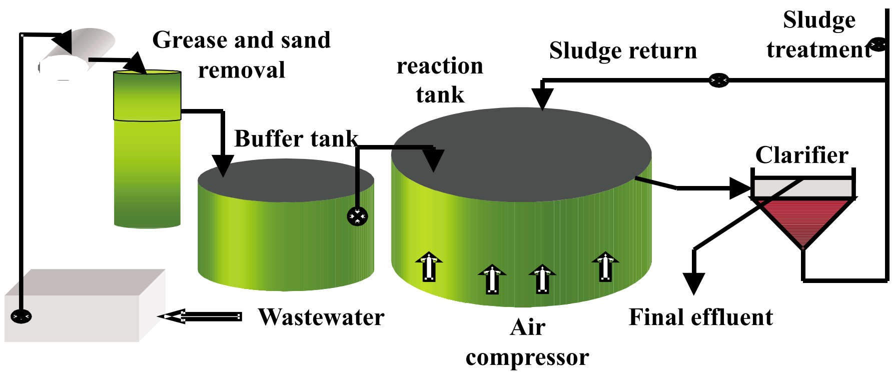

Figure 1 Schematic representation of the plant

Table 1 Main characteristics (24 h sampling) of the slaughterhouse effluent feeding the aeration tank

	Concentrations
Total COD (g/l)	5.2
Soluble COD (g/l)	2.7
SS (g/l)	1.5
VSS (g/l)	1.36
Ammonium NH_4^+-N (mg/l)	170
Total Kjeldahl nitrogen (mg/l)	358
NO_3^-–N (mg/l)	2.2

provided by a compressor. Supplying 8.42 m^3/min of air through 180 air diffusers, the operation time and frequency of this blower was managed by a simple timer.

Results and discussion

By using the "INFLEX" system (Ferrand *et al*., 1998), a control system based on detection of bending points, the diagnosis of the process state was carried out over one month. Flow rate perturbations were particularly noticeable. From the data obtained during this preliminary phase, the control strategy was elaborated and implemented with a programmable controller. The energy consumption and the plant performance regarding the removal of organic and nitrogenous pollution were quantified and compared for both conditions. Finally, pure oxygen was implemented on the aeration tank to provide more oxygen during the highly loaded period. Therefore it was important to test the behaviour of the control system in that case.

Bending point detection

At the beginning of the study, switching off and on of the aeration was performed by a timer and the anoxic time/aeration time ratio was fixed at 1 h/1 h. No adaptative control was then used. In a first step, the feasibility of bending point detection was assessed in order to know if the "INFLEX" control could be applied. Figure 2 gives the characteristic time-course of the nitrogen species, and of oxygen concentrations and ORP in the reaction tank.

The process was continuous and so ammonia, organic nitrogen and a small amount of nitrate were continuously fed into the tank. Each hour, the aeration was switched on or off, allowing nitrification and denitrification reactions to occur successively.

Phase A of Figure 2 corresponds to the aerated phase, during which nitrification took place. It is divided into A1 and A2. The distinction between A1 and A2 comes from the break in the nitrate production rate because of the rapid decrease in the nitrification rate when ammonia becomes limiting for the autotrophic biomass. Phase B corresponds to the anoxic phase (no aeration), where denitrification took place. Moreover, during this phase, ammonia from the feeding flow accumulated. During phase C, no more nitrate was present, and sulphate reduction took place (Plisson-Saune *et al*., 1996).

As can be seen in Figure 2, some bending-points appear on the ORP and DO curves. They characterise either the end of nitrification (α_{O2} point), or the end of denitrification (χ point). These characteristic bending points can therefore be used for real-time control implementation.

Diagnosis of the plant state

The plant feeding states were followed for one month. Plant feeding showed a weekly cycle which could be explained by the production in the industry. Representative operation of the

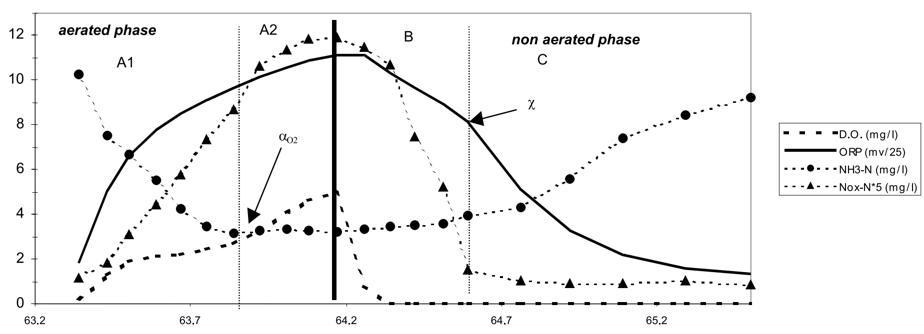

Figure 2 Characteristic profiles for nitrogen species concentrations, DO and ORP in the aeration tank (anoxic time/aeration time =1 h/1 h)

plant is described for one week of February with the following steps: 7th February, a Sunday, was a period of no work. The buffer was empty, the load was zero and only endogenous activity still remained. The production started again on Monday 8th and the organic load greatly increased. From Tuesday to Thursday the organic load was approximately constant and the buffer was filled. On 11th, the feed flow rate was doubled in order to avoid buffer tank overflow. Figure 3 presents the time courses of ORP and DO measured in the reaction tank over one week. The anoxic time/aeration time ratio was 1 h/1 h and was fixed by a timer.

ORP and DO are high during the low loaded period and decrease during the period of higher load. The profiles of the two probe responses follow the plant loading rate. As the organic load of the plant increases, DO concentration decreases and negative ORP values occur. These profiles are now being studied more accurately to better understand the relations between the probe responses and process performance. The first phase studied corresponds to the end of a weekend (Sunday). The time course of the DO, ORP and air flow rate are given in Figure 4 for this period.

The buffer tank was empty and the reaction tank was not fed. When the compressor was turned on, oxygen increased rapidly to a DO value of 5 mg/l. ORP value always remained positive even at the end of the non-aerated phase. No bending point appeared on the ORP curve or the DO curve and the DO concentration was high. This is characteristic of an over aerated state. Nitrogen ammonium and nitrate were not detected in the treatment plant effluent.

The second phase corresponds to the beginning of the week (Monday) but a few hours after the beginning of production at the slaughterhouse. So reaction tank feeding had begun a few hours before. The feed flow rate was 2 m^3/h and the organic loading rate was 0.062 kgCOD/kgVSS.d. Figure 5 gives the variation of ORP, DO and the aeration time -during this phase.

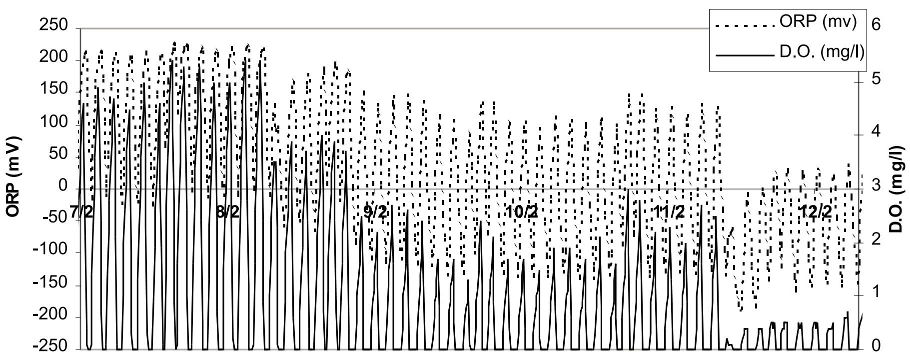

Figure 3 Variation of ORP and DO measured in the reaction tank over one week

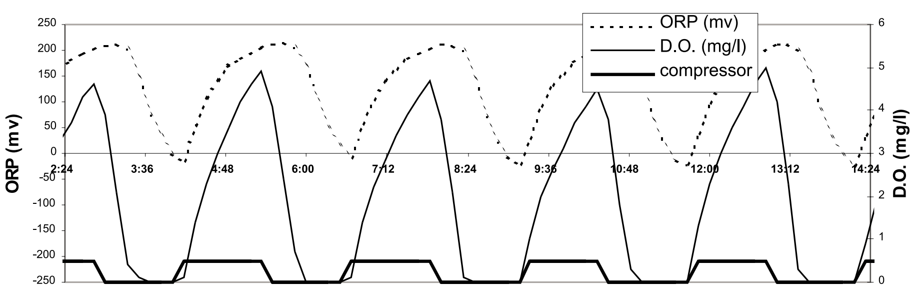

Figure 4 Variation of ORP and DO measured in the reaction tank Sunday (7/2). The anoxic time/aeration time ratio was 1 h/1 h and was fixed by a timer

Maximal DO concentration reached 2 mg/l and ORP varied regularly from –140 mV and +140 mV. The bending point alpha, characteristic of the end of the nitrification of the nitrogen previously accumulated, appeared systematically on both the DO and ORP curves. However the bending point alpha on the ORP curve was less pronounced. Indeed, ORP is linked to DO by a logarithmic relation (Paul *et al*., 1998). Therefore, for high dissolved oxygen concentrations (>2 mg/l), a small variation on oxygen profile may not be visualised on the ORP profile. This means that the a point on ORP (α_{ORP}) will be detected only if the oxygen level is suited to the feed load and more precisely to the oxygen demand (the best working range is DO<1mgO_2/l). Complete nitrification was reached.

In the anoxic phase, the bending point χ was observed systematically and without problem on the ORP curve, pointing out nitrate exhaustion (end of denitrification).

The third phase corresponded to the period of the week where the feed flow rate is increased by a factor two (middle of the week) (Figure 6). The organic loading rate was 0.124 kgCOD/kgVSS.d. DO remained low (DO<1mg/l) throughout the aeration time and ORP was always negative.

The bending point α was not present either on the DO curve or on the ORP curve. From that result, it was deduced that the nitrification was incomplete and ammonia measurements in the reactor at the end of the aerated phase confirmed this. During the anoxic phase, the bending point χ was observed very early on the ORP curve, pointing out nitrate exhaustion. It was then concluded that nitrification rate was limited by too low a DO concentration due to the high load applied with respect to the aeration capacity. The system was under-aerated.

The first part of the study provides a precise diagnosis of the operation of this treatment plant by the analysis of the ORP and DO signals. Whatever the organic load, the total disappearance of ammonia during the aerobic phase is related to an inflexion point on the DO and/or ORP signals, and the total disappearance of nitrates during the anoxic phase is related to an inflexion point on the ORP signal. It is particularly easy to estimate the level of nitrogen treatment actually achieved and the oxygen requirements, and to detect the over- or under-oxygenated phases. To summarize, most malfunctions and problems are revealed by this analysis.

"INFLEX" control implementation

The treatment plant needed to face many variations even though the buffer tank reduced the perturbations. In that context, a dynamic control of the aeration should improve treatment reliability or energy saving. Therefore automatic control based on the use of the bending point detection to turn the aeration on and off was implemented at the slaughterhouse treatment plant. Figure 7 shows the dissolved oxygen concentration over one week.

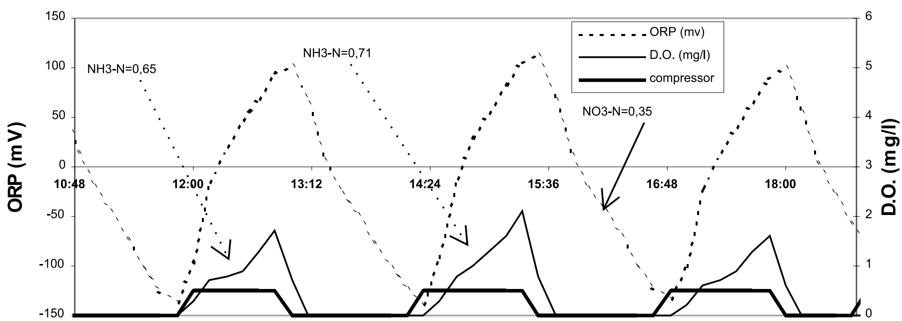

Figure 5 Variation of ORP and DO measured in the reaction tank during the Monday (8/2). The anoxic time/aeration time ratio was 1 h/1 h and was fixed by a timer

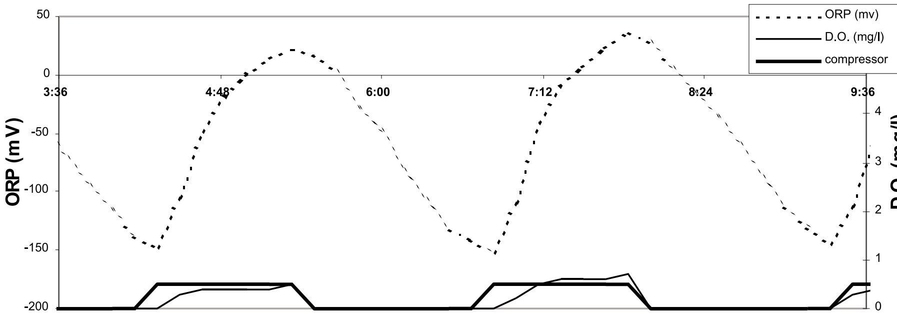

Figure 6 Time courses of ORP and DO measured in the reaction tank after the load increase. The anoxic time/aeration time ratio was 1 h/1 h and was fixed by a timer

First, it can be observed that the bending point α on the DO curve is well detected by the "INFLEX" control. If only ORP were used for switching off the aeration, the "INFLEX" control would not be reliable. Second, the behaviour of the aerated time/non aerated time ratio can be studied. During period 1 this corresponds to a low plant loading rate, the "INFLEX" control increases the global duration of the anoxic time. The aerated time/non-aerated time ratio is 0.44, which is a low value. It means that aeration time has been decreased and adapted to the requirement.

During period 2, the load rate increases and corresponds to the design load. The "INFLEX" control then increases the aerated time/non-aerated time ratio, which stabilises to a value close to 1. It should be noted that, in the slaughterhouse wastewater under study, the COD quality allowed good denitrification.

During period 3, a high load is applied to the biological tank. The "INFLEX" control again shows its adaptive nature. The aerated time/non-aerated time ratio is increased to 1.13.

Table 2 compares the aeration time and the electricity consumption for aeration over one week for the plant with or without the "INFLEX" control.

In addition, using the "INFLEX" control, the aeration time and the electricity consumption were decreased by around 30%. The operation time of the pump for MLSS recirculation also decreased. Indeed, as nitrate removal was complete, denitrification no longer occurred in the settler. Therefore, sludge recirculation could be decreased, improving sludge extraction.

The treatment performance is also compared between the two systems. Table 3 presents the removal yield for different pollution criteria and nitrogen concentrations in the effluent for both control systems. Removal yields are similar for both control systems. Nitrate concentration is slightly lower in the case of the "INFLEX" control.

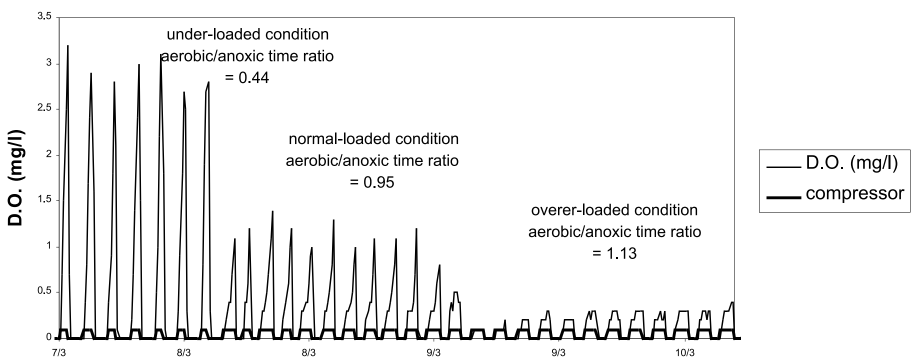

Figure 7 D.O. profile for one week of automatic control

Table 2 Aration time and electricity consumption for aeration over one week for the plant with or without the "INFLEX" control

	Work time per week of aeration device	Power consumption (kw/week)
Without aeration monitoring	112 h	1008
With aeration monitoring	80 h	720

When a plant is subjected to load perturbations, a dynamic control that manages the switching off and on of the aeration is required. Indeed, it has been shown that, with use of the "INFLEX" control, 30% energy saving can be reached while keeping good performance for COD, SS and nutrient removal. During the high load period (middle of the week), a lack of oxygen supply was evidenced. Therefore, it was decided to boost the aeration by using pure oxygen. The question of the control behaviour was posed.

Effect of pure oxygen

Pure oxygen is often used for aeration to upgrade under-aerated treatment plants. However, when pure oxygen is used alone, a significant pH decrease is observed during nitrification and the question of the bending point detection must be stressed.

Using pure oxygen alone, the pH mean value in the aerated tank was lower than when air was used for aeration. Indeed, the gas volume injected, and so the ventilation coefficient, was lower in the case of pure oxygen. Therefore, the CO_2 produced by the microorganisms was not sufficiently removed from the liquid, leading to the pH decrease. In the case of our study on slaughterhouse effluent treatment, the pH decrease was large and a pH of 6.5 was reached rapidly. Nitrification was then inhibited. Different strategies were therefore imagined to cope with this problem.

The first solution consisted of alternating aeration by air and pure oxygen. The alternation between the two aeration systems was determined by pH evolution. When the pH value reached a low threshold value, aeration by air was switched on, and when pH reached the high threshold value, pure oxygen was injected. In our case, the two thresholds were fixed at 6.85 and 7, resulting in an alternation of one air phase to two pure oxygen phases. The second solution consisted of using air and oxygen together for aeration. The feasibility of the control strategy based on bending point detection was also checked. The use of pure oxygen with air did not perturb the bending point detection when over-aeration of the system was avoided. In that case again, the treatment performance remained very good. They are presented in Table 3.

Conclusion

In the case of food industry wastewater treatment, ORP and DO profiles can be used with success to turn the aeration on and off. The concept of bending point detection is valid because the appearance of bending points is linked to the major biological processes occurring in the nitrogen removal. Therefore, a precise diagnosis of the process state of this type

Table 3 Comparison of average performance for different pollution criteria in the effluent for both control systems

	Timer (1 h/1 h)	Aeration monitoring with air	Aeration monitoring with pure oxygen
COD	97.0%	97.5%	97.8%
TKN	96.9%	97.2%	97.8%
NH3-N	98.3%	98.9%	99.1%
NO3-N	3.5 mgN/l	2.1 mg N/l	1.8 mg N/l

of treatment plant is possible. The nitrogen elimination level can be estimated and operation problems can be detected. The use of both ORP and DO signals are determinant for good and reliable diagnosis and control.

For the treatment plant concerned, the implementation of the "INFLEX" control led, in our case, to a 30% saving on the energy required for aeration without any detrimental effect on treatment efficiency. This was due to the adaptive nature of this control compared to the use of a simple timer. The more perturbed the system, the more useful the "INFLEX" control.

The use of pure oxygen, which was required when under-aerated conditions occurred in the reaction tank, did not change the efficiency of the "INFLEX" control but the pH variations had to be taken into account in the management of the control.

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