An aerated control strategy for oxidation ditch processes based on online oxygen requirement estimation

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ABSTRACT

A feedforward-feedback aeration control strategy based on online oxygen requirements (OR) estimation is proposed for oxidation ditch (OD) processes, and it is further developed for intermittent aeration OD processes, which are the most popular type in Japan. For calculating OR, concentrations of influent biochemical oxygen demand (BOD) and total Kjeldahl nitrogen (TKN) are estimated online by the measurement of suspended solids (SS) and sometimes TKN is estimated by NH4-N. Mixed liquor suspended solids (MLSS) and temperature are used to estimate the required oxygen for endogenous respiration. A straightforward parameter named aeration coefficient, Ka, is introduced as the only parameter that can be tuned automatically by feedback control or manually by the operators. Simulation with an activated sludge model was performed in comparison to fixed-interval aeration and satisfying result of OR control strategy was obtained. The OR control strategy has been implemented at seven full-scale OD plants and improvements in nitrogen removal are obtained in all these plants. Among them, the results obtained in Yumoto wastewater treatment plant were presented, in which continuous aeration was applied previously. After implementing intermittent OR control, the total nitrogen concentration was reduced from more than 5 mg/L to under 2 mg/L, and the electricity consumption was reduced by 61.2% for aeration or 21.5% for the whole plant.

Key words | aeration control, energy saving, nitrogen removal, online measurement, oxidation ditch

INTRODUCTION

The oxidation ditch (OD) process was developed by Pasveer in the Netherlands in 1953 to provide low cost treatment for small communities. As the OD process is operated with long hydraulic retention times (HRTs) and high solids retention times, it has the ability to nitrify and denitrify within a single tank as long as the aeration operation is suitable and the temperature is not too low.

From the viewpoint of nitrogen removal and energy saving, the OD process has three possible advantages (Rittmann & Langeland 1985). First, the very high recycle rate of mixed liquor provides NO3-N for anoxic oxidation of incoming biochemical oxygen demand (BOD). Second, the flexibility in oxygen transfer capability (caused by changing the water level, varying aerator speed, or turning individual aerators on and off) allows careful matching of oxygen supply (OS) to the oxygen requirement (OR). Third, the distance and time of travel between aerators provides for oxygen depletion and establishment of alternating aerobic and anoxic zones.

The first OD plant in Japan was Yumoto wastewater treatment plant (WWTP) starting operation in 1966, which will be described in detail in this paper. Right now there are about 950 OD plants in Japan. Among them, the main types of aerators, derived from statistics on Japanese sewerage system (Japan Sewage Works Association 2006, 2010), include vertical shaft type (44% on plant number), screw type (31%), brush type (16%) and diffused aeration (with submerged mixer) type (7%). Intermittent aeration is applied in most of them. Many studies have proven that complete nitrification and denitrification can be achieved in the OD process with intermittent aeration, under the conditions that aerobic solids retention time (ASRT) is large enough to promote nitrification (Sakai et al. 2002) and anoxic operation is properly performed to accomplish denitrification (Inomae et al. 1987; Dayton and Knight, Ltd 2001).

More and more OD plants in Japan are managed under mobile operation and maintenance (O&M), which can save costs compared with resident O&M. This leads to an increasing need for reliable automatic control technology that should deliver the required effluent quality while realizing energy saving. However, most of the OD plants in Japan are operated by empirically scheduled on-off patterns. Obviously, this kind of operation cannot deal with a large influent fluctuation satisfactorily.

To provide a method for ensuring effluent quality and saving energy, a feedforward-feedback aeration control strategy based on online OR estimation (for simple it is referred to as ‘OR control’) is developed. Furthermore, OR control is developed for intermittent aeration, which is the most popular method applied in OD plants in Japan. The OR control strategy has been implemented at a number of full-scale OD plants, covering different types of aerators, and encouraging results have been obtained. The control algorithm, the simulation results and part of the OD plant data are presented in this paper.

**ALGORITHM AND SYSTEM CONFIGURATION OF OR CONTROL**

A number of studies have been carried out in control of effluent NH₄⁻N using feedforward-feedback control strategies (Ingildsen et al. 2002; Vreco et al. 2006; Thornton et al. 2010). In these studies, only influent NH₄⁻N was used for feedforward control of aeration, although influent BOD is also one of the most important factors of OR and it does not always follow the same time course as NH₄⁻N. In this study, the feedforward calculation is intended to be as precise as possible to match the supply to the actual requirement of oxygen. Thus, both influent BOD and total Kjeldahl nitrogen (TKN) are estimated online.

In planning of an activated sludge WWTP, the OS capacity of aerators is designed to meet the OR for treating the influent loadings, and OR is calculated offline with Equation (1). In this study, the idea of OR calculation is adopted for aeration control as described below.

When the removal of organic carbon and nitrogen (complete denitrification) is taken into account, the total OR can be expressed as given in the Japanese design guideline for sewage system (Japan Sewage Works Association 2001).

\[
\text{OR} = D_B + D_N + D_E + D_O \quad [\text{kgO}_2/\text{day}] \tag{1}
\]

where \(D_B\), \(D_N\), \(D_E\) and \(D_O\) represent the OR for BOD oxidation, nitrification, endogenous respiration, and compensation for DO outflow, respectively. The three items are expressed as follows, while \(D_O\) is not considered here since it is usually negligible compared to other items:

\[
D_B = A \times F_{\text{in}}(Y_B \times \text{BOD} - K \times Y_N \times \text{TKN}) \quad [\text{kgO}_2/\text{day}] \tag{2}
\]

\[
D_N = 4.57 \times F_{\text{in}} \times Y_N \times \text{TKN} \quad [\text{kgO}_2/\text{day}] \tag{3}
\]

\[
D_E = B \times V_A \times \text{Y}_{\text{ML}} \times \text{MLSS} \quad [\text{kgO}_2/\text{day}] \tag{4}
\]

where the parameters are defined as follows. \(A\): oxygen required for unit BOD removal, (0.5 to 0.7) \(\text{kgO}_2/\text{kgBOD}\), \(F_{\text{in}}\): influent flow, \(\text{m}^3/\text{day}\), \(Y_B\): ratio of BOD removal to influent, \(K\): BOD consumed by unit denitrified nitrogen, (2 to 3) \(\text{kgBOD/\text{kgNO}_3-N}\), TKN: concentration of influent Kjeldahl nitrogen, \(\text{mg}/\text{L}\), \(Y_N\): ratio of TKN removal to influent, which is calculated by subtracting the TKN in waste sludge and effluent from influent, according to actual data or empirically, \(B\): endogenous respiration coefficient, (0.05 to 0.15) \(\text{kgO}_2/\text{kgMLVSS/day}\) (MLVSS = mixed liquor volatile suspended solids), \(V_A\): volume of aerobic zone, \(Y_{\text{ML}}\): proportion of MLVSS to mixed liquor suspended solids (MLSS).

Because the endogenous respiration coefficient, \(B\), varies in a broad range and is considered to be greatly affected by temperature, the following method is introduced referring to activated sludge model ASM3 (Henze et al. 2000). \(B\) at any temperature is calculated by the following equation:

\[
B(T) = B(20^\circ \text{C}) \times \exp(\theta_T \times (T - 20^\circ \text{C})) \quad [\text{kgO}_2/\text{kgMLVSS/day}] \tag{5}
\]

where \(\theta_T\) is defined as \(\ln(B(T_1)/B(T_2))/(T_1 - T_2)\). According to ASM3, the aerobic endogenous respiration rate of heterotrophic organisms at 20 °C is two times that at 10 °C; the value of \(\theta_T\) is easily calculated to be 0.06932. Hence, Equation (5) is reformed as follows:

\[
B(T) = B(20^\circ \text{C}) \times \exp(0.06932 \times (T - 20^\circ \text{C})) \quad [\text{kgO}_2/\text{kgMLVSS/day}] \tag{6}
\]

To calculate OR online, it is necessary to measure influent flow \(F_{\text{in}}\), concentrations of BOD and TKN of influent, MLSS and temperature of reaction tank. \(F_{\text{in}}\), MLSS and temperature can be easily measured online. The problem is that influent BOD and TKN concentrations are very difficult to measure online. According to the authors’ investigations, influent BOD and TKN are commonly well
correlated to suspended solids (SS) and NH$_4$-N, respectively. In many OD plants, TKN is also well correlated to SS. This means that we can estimate the concentrations of BOD and TKN by measuring SS and NH$_4$-N, or even just SS, using online in-situ sensor measurements directly from the process. This solved the above problem and the aeration control strategy based on online OR estimation became practical.

In practice, to prevent over-reaction in control to changes of influent concentration, the concepts of short-term influent OR (OR$_\text{in S}$) and long-term OR (OR$_\text{in L}$) are introduced. They are similar to, but different from, ready biodegradable substrate (S$_S$) and slowly biodegradable substrate (X$_S$) defined in ASM. OR$_\text{in S}$ refers to the part of OR from substrates that are utilized by microorganisms in a short time after flowing into the reaction tank, like soluble BOD and NH$_4$-N. OR$_\text{in L}$ refers to the part of OR from those which are treated gradually, like slowly biodegradable organic matter.

The system configuration of OR control strategy is shown in Figure 1. The aeration manipulation variables (revolving speed rpm, on-off instruction, etc.) are calculated referring to OS performance database, which is provided by manufacturers or measured onsite.

For the purpose of stabilizing the water quality, feedback tuning of aeration parameters is incorporated by measuring DO concentration, NH$_4$-N concentration, or pH value of reaction tanks. A long-term parameter named aeration coefficient, Ka, is introduced as the only parameter that can be tuned automatically by feedback control or manually by the operators. Ka is utilized as follows:

$$\text{OR} = \text{Ka} \times \text{OR}_{\text{calc}} \ [\text{kgO}_2/\text{day}]$$  \hspace{1cm} (7)

where OR$_{\text{calc}}$ is the calculated value described above.

The shape of time course curve of OR is determined by parameters like $B(T)$ and ratio of OR$_\text{in S}$, etc., for which only initial setting and occasional adjustment are required. However, the overall amount of OR is determined by the aeration coefficient, Ka. Automatic feedback tuning of Ka is usually implemented once a day. When Ka is tuned manually, it is very straightforward. For example, you can multiply the present value of it by 1.05 if you want to increase OS by 5%.

For the control of the OD process in which intermittent aeration is necessary, like most OD plants in Japan, it is necessary to find a method to determine when aerators should be turned on or off according to the varying loadings. As shown in Figure 2, integration calculation of difference value between OR and OS (ΔOR$_\text{OS}$) is introduced to the OR control strategy. With the inflow of wastewater to the aeration tank, the integrated ΔOR$_\text{OS}$ value increases and the aerator is set on when this integral value reaches a trigger point (set value). In contrast, with the continuous supply of oxygen to the aeration tank, the integrated ΔOR$_\text{OS}$ value decreases, and the aerator is turned off when the integral value decreases to zero. In this way, the intervals of on and off of aerators are automatically adjusted. For example, at midnight, when influent loading is low, the off-time will become longer and on-time shorter than those in the morning when the influent loading is high.

**SIMULATION WITH ASM**

To examine the proposed OR control strategy, computer simulation with activated sludge model ASM2d (Henze et al. 1999) was performed for an OD plant, Agatsuma WWTP, which has a 1,800 m$^3$/day capacity. The simulation software WEST (MOSTforWATER NV, Kortrijk, Belgium) was used for model building, simulations and
parameter estimations. This simulation was performed to examine the effect of aeration operation on the effluent quality when the influent loading reaches the designed capacity.

For characterization of the wastewater, the influent was sampled once every 2 hr during a period of 24 hr in Agatsuma WWTP. The influent wastewater was characterized in terms of ASM2d components using the STOWA protocol with modification (Roeleveld & van Loosdrecht 2002). A 0.1 μm filter was used to separate soluble and particulate compounds. The continuous stirred tank reactor (CSTR) in series was utilized for process configuration. Almost all of the original model parameters were adopted from ASM2d, except that $K_{O2}$ and $K_{NH4}$ of $X_{AUT}$ were changed from 0.5 to 0.1 and 1.0 to 0.2, respectively, together with $K_{NO3}$ being changed from 0.5 to 0.2.

Performance of the OR control was verified against diurnal fluctuations of influent flow and concentrations. For comparison, conventional timer operation with fixed aeration interval was simulated under the conditions that the total daily aeration time was the same as OR control. The daily average flow $F_{in}$ was set to 1,800 m$^3$/day (HRT = 24 hr) and the total daily aeration time was set to 12 hr for both cases. The oxygen transfer coefficient, $K_{L,a}$, was calculated offline based on OR control algorithm with MS Excel and used as input data to the simulator.

Part of the simulation results is shown in Figure 3. Although effluent NO$_3$-N concentrations were comparable in both strategies, effluent NH$_4$-N concentrations showed a big difference. Under the fixed-interval aeration, NH$_4$-N concentration increased significantly during high loading hours, as a result of insufficient supply of oxygen. In contrast, the OR control produced more stable effluent NH$_4$-N concentrations because adequate amount of oxygen was supplied based on OR estimation.

**PERFORMANCE OF OR CONTROL IN FULL-SCALE OD PLANTS**

Intermittent OR control strategy has been applied to seven full-scale OD plants until recently. In this section, results obtained in these plants will be presented first and Yumoto WWTP will be exhibited as a concrete example, subsequently.

The earliest OR control system was implemented at Agatsuma WWTP in January 2005, shortly after it was put into operation, and the others were introduced in the recent 3 years. Some total nitrogen (TN) concentration data of the effluent are presented in Figure 4. Basically all of the data were collected for 2 years, 1 year before and after introduction of OR control. If insufficient data in a plant were available for 2 years, only the latest available data were utilized. Except for Yumoto WWTP, all other...
plants had been operated under intermittent aeration before OR control introduction.

TN under and before OR control was compared, and countrywide average derived from statistics on Japanese sewerage system (Japan Sewage Works Association 2010) was employed for reference. The results show that improvement was observed in every plant by OR control (except Agatsuma, which had no data before OR control). This is because no over-aeration or under-aeration, which may cause incomplete denitrification or poor nitrification respectively, was observed in these plants after implementation of intermittent OR control.

For the purpose of giving a concrete example of applying intermittent OR control to an OD plant, Yumoto WWTP was chosen. Yumoto WWTP is located in a famous sightseeing spot of Japan, Nikko area, and is the oldest OD plant in Japan, operating from 1966. Wastewater from the neighbouring hot spring hotels is treated in this plant and effluent flows into the Lake of Yunoko.

There are only two sedimentation tanks for three ditches. The plant is almost in full loading by means of flow (HRT is near 24 hr), but the sedimentation tanks are too small to meet the need of solid–liquid separation. Therefore, flocculant is dosed to the system to promote the separation. This causes the problem that the brush type aerators cannot be stopped for a long time to prevent poor mixing of influent and the sludge. As a result, before intermittent OR control was implemented, continuous aeration was the only choice, which inhibited denitrification and as a result nitrogen could not be removed at all.

From 6 October 2010, OR control was introduced to this plant and intermittent aeration became possible. In this plant, OR control is carried out in the way that adequate oxygen is provided to remove BOD and nitrogen but aeration operation is under severe restrictions that both too long and too short intervals are not allowed.

An SS sensor was used to measure the influent SS and MLSS of No. 3 ditch. An ion-selective ammonium sensor made by WTW was used to measure NH₄⁻N concentrations in influent and in No. 3 ditch. Both SS and NH₄⁻N sensors were installed in a water quality measuring unit, which was designed to measure concentrations of multiple sampling points.

Influent BOD was estimated from SS, and TKN was estimated from NH₄⁻N based on pre-investigation. An example of diurnal variations of flow and influent SS and NH₄⁻N concentrations is given in Figure 5. As hot spring drainage flows into this plant, the influent concentrations are much lower than common plants. It is shown that the influent loadings fluctuated greatly, and the time courses of NH₄⁻N and BOD differed from each other. The operational result of aerators based on intermittent OR control is given in Figure 6. OR control was implemented at No. 3 ditch, while No. 1 and No. 2 ditches were set to follow No. 3 ditch. The on-and-off of two aerators in No. 3 ditch, 3_1 and 3_2, which were put into operation alternatively, followed the integration results of ΔOR – OS as has been explained in the algorithm of intermittent OR control. The example trend of aeration time together with influent SS and NH₄⁻N concentrations in November 2010 is given in Figure 7. It clearly shows that the aeration time closely followed the influent loadings, which was greater at weekends than in weekdays.

The variation of TN, NH₄⁻N and NO₃⁻N concentrations in effluent and the electricity consumptions in the period from July 2010 to March 2011, when water qualities were analysed more frequently than usual for the purpose of investigation, are shown in Figures 8 and 9, respectively. Because there were no independent power records for aerators, the electricity consumption for aeration was calculated from the time records of aerators. Both nitrogen removal and energy saving were greatly improved by intermittent OR control. The TN

Figure 5 | Diurnal variations of flow and concentrations.

Figure 6 | The operational result of aerators based on intermittent OR control.
The concentration was reduced from more than 5 mg/L to under 2 mg/L. The electricity consumption was reduced by 61.2% for aeration or 21.5% for the whole plant. By applying OR control, the competing demands of removing nitrogen and ensuring solid–liquid separation were satisfied and energy saving was realized accordingly.

**CONCLUSIONS**

A feedforward-feedback aeration control strategy based on online OR estimation is developed for OD processes, and it is further developed for intermittent aeration processes by introducing integration calculation. The feedforward calculation in OR control is intended to supply oxygen as precisely as possible to match the requirement.

For calculating OR, the influent flow, MLSS and temperature of reaction tank are measured directly, but concentrations of influent BOD and TKN are estimated from SS, and sometimes TKN is estimated from NH₄-N. Both SS and NH₄-N are measured online with sensors. Temperature is used to estimate the required oxygen for endogenous respiration.

A straightforward parameter, named aeration coefficient, Ka, is introduced as the only parameter that can be tuned automatically by feedback control or manually by the operators.

Simulation with ASM was performed and satisfying result of OR control strategy was obtained in stabilizing water quality.

The OR control strategy has been implemented at seven full-scale OD plants until recently and improvements in nitrogen removal are obtained in all these plants.

Intermittent OR control strategy was implemented at Yumoto WWTP, in which continuous aeration was the only choice previously because of the facility restrictions. After implementing intermittent OR control, the TN concentration was reduced from more than 5 mg/L to under 2 mg/L and the electricity consumption was reduced by 61.2% for aeration or 21.5% for the whole plant.

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