Feasibility of controlling nitrification in predenitrification plants using DO, pH and ORP sensors

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Abstract Experimental studies were carried out on a bench-scale nitrogen removal system with a predenitrification configuration to gain insights into the spatial and temporal variations of DO, pH and ORP in such systems. It is demonstrated that these signals correlate strongly with the operational states of the system, and could therefore be used as system performance indicators. The DO concentration in the first aerobic zone, when receiving constant aeration, and the net pH change between the last and first aerobic zones display strong correlations with the influent ammonia concentration for the domestic wastewater used in this study. The pH profile along the aerobic zones gives good indication on the extent of nitrification. The experimental results also showed a good correlation between ORP values in the last aerobic zone and effluent ammonia and nitrate concentrations, provided that DO in this zone is controlled at a constant level. These results suggest that the DO, pH and ORP sensors could potentially be used as alternatives to the on-line nutrient sensors for the control of continuous systems. An idea of using a fuzzy inference system to make an integrated use of these signals for on-line aeration control is presented and demonstrated on the bench-scale system with promising results. The use of these sensors has to date only been demonstrated in intermittent systems, such as sequencing batch reactor systems.

Keywords Denitrification; DO; fuzzy control; nitrification; ORP; pH

Introduction

With the development of reliable on-line nutrient analysers, numerous control strategies have been proposed in the literature for the control of biological nitrogen removal systems based on ammonia and nitrate measurement (Olsson *et al.*, 2005). These systems have huge potential for large wastewater treatment plants. Wide application of nutrient sensor based control systems to small wastewater treatment plants may, however, prove difficult due to the relatively high capital and maintenance costs of the nutrient analysers. In this regard, simple sensors such as those for DO (dissolved oxygen), pH and ORP (oxidation-reduction potential) measurements offer attractive cheap alternatives.

The use of DO, pH and ORP for the on-line control of intermittent systems such as sequencing batch reactors (SBR) has been investigated and demonstrated by many researchers in recent years. At the end of denitrification there typically appear 'nitrate knee' in the ORP profile and 'nitrate apex' in the pH profile (Cho *et al.*, 2001; Paul *et al.*, 1998). Similarly, there is often appearance of 'ammonia break point' in the DO and ORP profiles, and 'ammonia valley' in the pH profile at the end of nitrification (Chang and Hao, 1996; Hao and Huang, 1996). These bending points have been used in control

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system design by many researchers (see, for example Yu *et al.*, 1998). However, the use of these simple sensors in continuous processes has not been widely reported to date.

The objective of this research is to study if the DO, pH and ORP sensors can be used as alternatives to the ammonia and nitrate analysers to provide support to the on-line control of continuous systems performing nitrogen removal. To accomplish this, a series of experimental studies was undertaken on a bench-scale system to establish the dependency of DO, pH and ORP on the influent characteristics and process operation, and to investigate the feasibility of using these signals as indicators for the system performance. The idea of using a fuzzy inference system to make an integrated use of these signals for on-line aeration control is discussed and demonstrated on the bench-scale system with promising results. Fuzzy control is believed an attractive alternative to conventional PID control systems due to its capability to cope with inaccurate and incomplete information, and has attracted considerable attention in the control of wastewater systems (Kalker *et al.*, 1999; Galluzzo *et al.*, 2001; Peng *et al.*, 2003).

Materials and methods

Reactor system

Experiments were carried out on a bench-scale predenitrification reactor system (Figure 1). The reactor with a total working volume of 49 L consists of seven zones separated by baffles. Each zone has a volume of 7 L. The cylindrical settler has a diameter of 25 cm and a total volume of 20 L. The first two zones were typically operated as anoxic reactors, while the remaining five as aerobic ones with aeration manipulated separately. Zones 2–4 may be operated as either anoxic or aerobic reactors as required. Each zone is equipped with on-line DO (WTW inoLab Oxi level2 oxygen meters), pH and ORP (HANNA) sensors. The signals from these sensors were collected by a computer, which was also used to control the variable speed peristaltic pumps used for nitrate recirculation, sludge recycling and the wastewater feeding, stirrers in zones 1 to 4, and the aeration values in zones 2 to 7.All experiments were conducted and controlled at a temperature of 20–21°C. The solids retention time (SRT) was set to 12 days, leading to a mixed liquor suspended solids (MLSS) concentration of approximately 3000 mg/L throughout the experimental period. The nitrate recirculation flow rate and sludge recycling flow rate was 2.5 and 0.6 times of the influent flow rate, respectively. The reactor was operated into quasi-steady state before detailed experiments (described below) commenced. Samples were collected regularly from the reactor and the feed for the off-line measurement of ammonia, nitrate, nitrite, total nitrogen (TN), COD, BOD_5 and alkalinity according to standard methods (APHA, 1995).

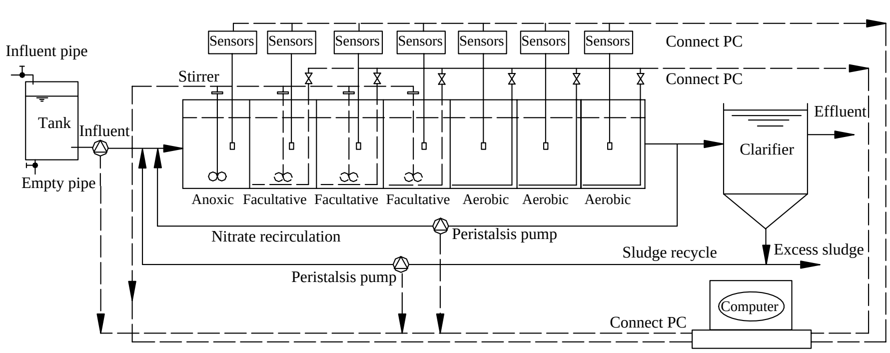

Figure 1 A schematic view of the bench-scale reactor system

Sludge and wastewater

The seeding sludge for the reactor was collected from the full-scale plant of Harbin Wenchang WWTP, which is a nitrogen removal plant with a predenitrification configuration. The reactor was fed with wastewater collected from an on-campus sewer line. A summary of the influent characteristics is given in Table 1. The wastewater was collected daily (at approximately the same time everyday). The influent flow was controlled at 150 L/d during the experiments, resulting in a hydraulic retention time (HRT) in the reactor of 8 h.

Experimental design

Five sets of experiments were carried out for the purpose of determining the correlations between DO, pH and ORP signals and the influent characteristics and system performance, and to test the control algorithm proposed. Each set involved a number of tests at different influent and/or operational conditions. In each test, the conditions required were applied for a period of 4 days before an intensive sampling campaign was carried out. The experimental conditions for each set of experiments are summarised in Table 2.

Results and discussion

Correlation between DO in the first aerobic zone and influent ammonia

As shown in Figure 2, the DO concentration in this zone, which received constant aeration, was found to be linearly dependent on the influent ammonia concentration with an R^2 value of 0.80. DO in this zone also tended to decrease with increased influent COD concentration. However, this dependency was not as strong as in the case of ammonia. This is mainly because of the fact that, in the predenitrification process, most readily biodegradable COD was consumed in the anoxic zones as the energy or carbon sources for denitrifiers, with only little COD spilled to the aerobic zones. As a result, influent COD had little influence on the oxygen consumption rate in the first aerobic zone and hence a minor impact on the DO concentration in this zone. These results suggest that it would be feasible to use the DO concentration in the first aerobic zone, as an alternative to the influent ammonia measurement, as feedforward information for the control of the airflow rates to the aerobic zones.

Correlation between the variations of pH in aerobic zones and influent ammonia

Figure 3 shows that the pH variation across the aerobic zones is positively correlated with the influent ammonia concentration. Owing to the generation of hydrogen ions (H^+) by nitrification, higher influent ammonia resulted in larger pH variations in aerobic zones. Therefore, dynamic aeration control according to the variation of ammonia loading measured as pH variation should be possible.

The spatial pH profile in aeration zones

Figure 4 gives typical profiles of COD, NH_4^+-N, NO_3^--N, NO_2^--N, DO, ORP and pH along the reactor when fed with wastewater containing a medium level of ammonia (50–52 mg N/L). With COD and ammonia removed along the reactor, the ORP increased,

Table 1 Influent characteristics

Parameters	pH	COD (mg/L)	BOD5 (mg/L)	TN (mg/L)	NH_4^+-N (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	Alkalinity (mg/L)
Range	6.5–7.8	176–521	90–291	31–100	20–90	0.05–0.25	0.07–1.11	200–420
Mean	7.52	322	174	65	59	0.15	0.73	320

Table 2 Summary of experimental conditions

Set	Goal	Conditions
1	Correlation between DO in first aerobic zone and ammonia loading	Influent ammonia varied between 25 ~ 90 mg N/L; influent COD varied between 180 ~ 500 mg/L; the aeration in the first aerobic zone was maintained at 0.08 m^3/h; the DO concentration in other aerobic zones controlled at 2 mg/L
2	Correlation between pH change and ammonia loading	Influent ammonia varied between 20 ~ 100 mg N/L; influent COD at about 300 mg/L; DO in all the aerobic zones controlled at 2 mg/L
3	Spatial pH profiles at different conditions	Five influent conditions were used with influent ammonia concentration being: (1) 52 mg N/L; (2) 74 mg N/L; (3) 66 mg N/L; (4) 60 mg N/L and (5) 30 mgN/L. Influent COD varied around 300 mg/L. DO in all aerobic zones controlled at 2 mg/L
4	Correlation between ORP and DO, ammonia and nitrate in the last aerobic zone	In the DO study, DO in the last aerobic zone was controlled at different levels between 0–5 mg/L the influent ammonia concentration was at a normal level of 50–55 mg N/L. In the second part of the study, DO in the last aerobic zone was controlled at 1.5 mg/L. The influent ammonia was varied such that the effluent ammonia and nitrate varied in a relatively large range
5	Test the controller	Influent ammonia varied at between 20–85 mg N/L

while the pH increased from the first anoxic zone to the first aerobic zone (zone 3), then decreased till the sixth zone before increased again in the seventh zone. The 'valley' in zone 6 suggests that complete nitrification was achieved by this point. This is confirmed by the ammonia data, which was zero in zone 6. The results indicate that the aeration applied in this case was excessive and could therefore be reduced. The pH profile shown in Figure 4b is said to be of a descending-rising type.

Figure 5 shows four other types of pH profiles in aerobic zones. In Figure 5a, the pH rose in the first three zones and then decreased throughout the rest of the zones, suggesting nitrification occurred throughout all aerobic zones as confirmed by the ammonia data. The pH variation in aerobic zones was large (0.94) in this case. This was likely caused by the high influent ammonia concentration (measured as 74 mg N/L), in conjunction with the low alkalinity that did not allow for full nitrification (the alkalinity level in zone 7 was less than 10 mg/L). Additional alkalinity should have been added to the wastewater to achieve complete nitrification. This pH profile is of a descending type. The pH profile in Figure 5b showed a rising–descending pattern. It increased through the first four zones and then descended throughout the rest of the zones. The pH variation in aerobic zones was very small (only 0.05), which suggested a poor nitrification rate in the system. This was confirmed by the ammonia measurement, which showed a high level of

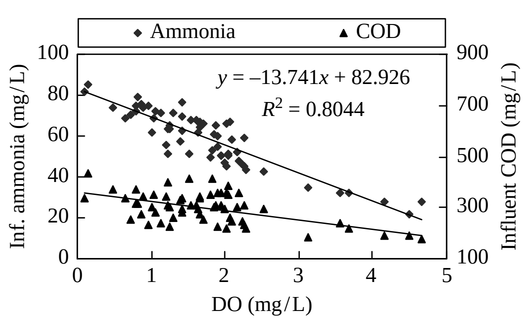

Figure 2 The correlation between DO in the first aerobic zone and influent ammonia & COD

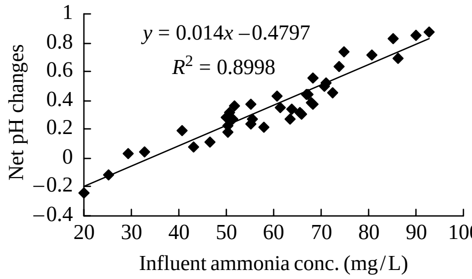

Figure 3 The correlation between pH variation in aerobic zones and influent ammonia

11 mg N/L in zone 7. In Figure 5c, the pH increased in the first four zones, then decreased reaching the lowest level in the fifth zone, before rising again (rising–descending–rising type). This 'valley' again corresponded to the depletion of ammonia in zone 5, as confirmed by the ammonia measurement. In Figure 5d, the pH increased throughout all zones (rising type). It was observed that influent ammonia nitrogen was low (27 mg N/L) in this case and full nitrification was achieved in the first two aerobic zones.

The complex pH variation along the aerobic zones is believed to be jointly caused by a number of factors. The two most pH-influencing processes are nitrification, which causes the pH to decrease, and CO_2 stripping, causing the pH to rise. Other processes include CO_2 production (causes pH to decrease) primarily due to endogenous carbon oxidation, and aerobic denitrification (pH rises) when DO is low. From the control point of view, the five types of pH profiles discussed above can be classified into two broad categories, that of a descending type (including both the descending type and the rising–descending type), indicating nitrification process was not completed in the reactor; and that of a rising type (the descending–rising type, rising–descending–rising type and the rising type), indicating that nitrification was completed in the zone with the lowest pH. The profile can, therefore, be used to adjust the aeration intensity applied to each of the aeration zones to allow nitrification to be completed in the desired zones (e.g. zone 6 or 7). As discussed above, the spatial pH profile also carries information about the level of alkalinity and ammonia nitrogen in the influent, which should also be useful for control.

Correlation between ORP and DO, ammonia and nitrate in the last aeration zone

Oxidation-reduction potential (ORP) is the electromotive force developed when oxidisers or reducers are present in aqueous solution. It is a comprehensive indicator of pH, COD, DO and NO_3^-/NH_4^+ concentrations. As seen in Figures 4 and 5, pH in the last aeration zone varied in a relatively small range (±0.3) when sufficient alkalinity was available in the influent, and there was hardly any biodegradable COD present in the last aerobic

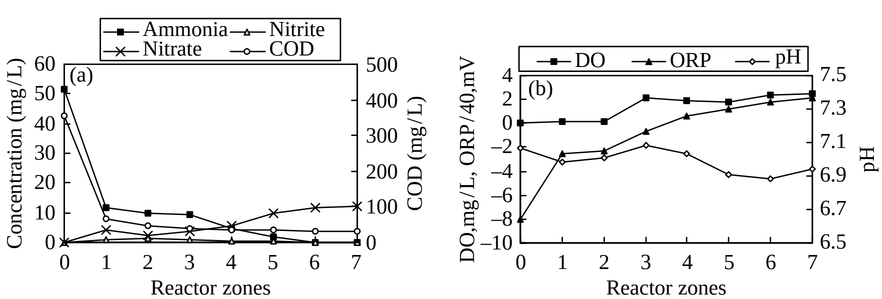

Figure 4 COD, ammonia, nitrite and nitrate concentrations, and the DO, ORP and pH values in different zones. '0' represents raw sewage, '1, 2, 3, 4, 5, 6, 7' are the zone numbers

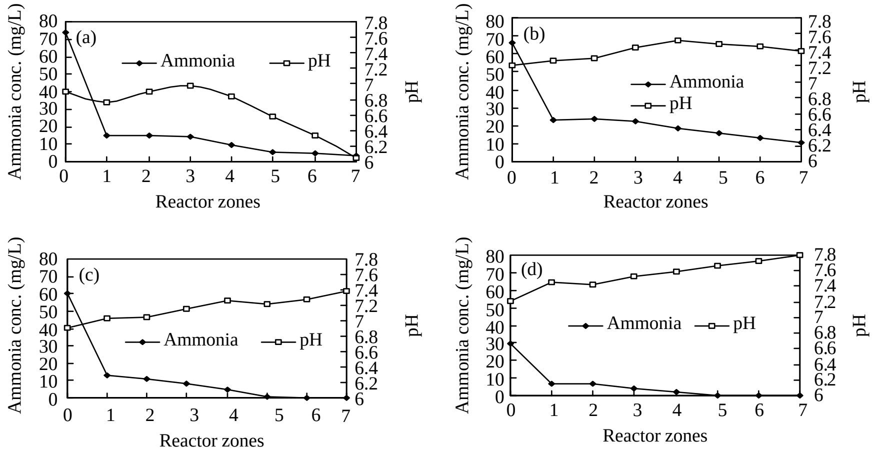

Figure 5 The other four types of pH profiles (a) descending; (b) rising–descending; (c) rising–descending–rising; and (d) rising

zone. Thus, the ORP in this zone was primarily determined by the DO and NO_3^-/NH_4^+ concentrations. It is known that ORP is strongly influenced by DO. This is confirmed by Figure 6, which was obtained through varying DO concentration in this zone while keeping the influent ammonia concentration at a normal level of 50–55 mg N/L. The ORP values increased logarithmically with the DO concentration.

A question of interest is if the ORP values could be used to give indication about the NO_3^--N/NH_4^+-N levels if DO is controlled to a constant set-point. Figure 7, which was obtained through varying the influent ammonia concentration while keeping the DO in the last aerobic zone at 1.5 mg/L, shows the correlation between ORP and the effluent ammonia and nitrate concentrations. It can be observed that at low levels ($<$60 mV), the ORP value is more influenced by the ammonia concentration; while at high levels, it is more determined by nitrate concentration. It is seen that an ORP value of higher than 70 mV corresponded to an ammonia concentration of less than 3 mg/L. When ORP exceeded 90 mV, ammonia was almost undetectable while nitrate concentration was relatively high. These experiments suggest that the aeration volume and aeration intensity to upstream aerobic zones should be controlled such that the ORP in the last aerobic zone is kept in the range of 70 ∼ 85 mV. One difficulty with this idea is that the ORP signal typically drifts significantly over time, which needs to be addressed.

A conceptual fuzzy inference system

The experimental results reported above suggested that it would be possible to design an on-line aeration control system based on the DO, pH and ORP signals for achieving

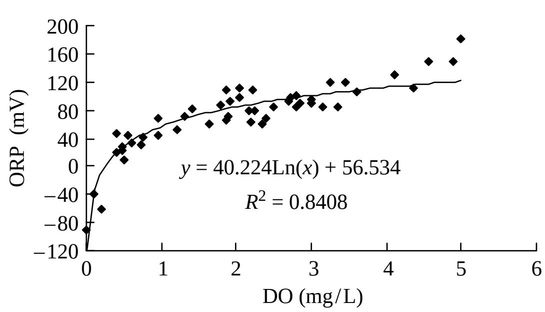

Figure 6 The correlation between DO and ORP in the last aeration zone

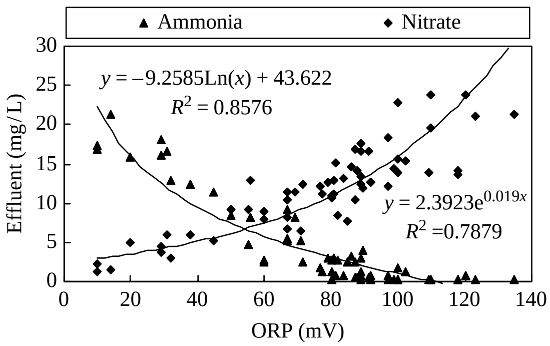

Figure 7 The correlation between ORP and ammonia and nitrate concentrations in the last aeration zone

satisfactory nitrification with minimized aeration costs. A fuzzy logic controller is proposed and shown in Figure 8. It needs to be highlighted that it is still a conceptual idea at this stage. Considerable improvement and fine tuning is still required for the method to be practical and useful. The primary aim was to quickly test the feasibility of using DO, pH and ORP signals for nitrogen removal control in continuous systems. The control system requires: (1) the airflow rate to the first aerobic zone is kept constant (at 0.08 m^3/h in the experimental studies reported below); and (2) the DO concentration in the last aerobic zone is kept at a constant level (1.5 mg/L is used in the study reported below). Further, the controller requires as parameters the upper and lower limits of ORP value in the last aerobic zone (suggested to be 85 and 70 mV, respectively), the upper and lower limits of DO concentration in aerobic zones other than the first or the last (suggested to be 3.5 and 0.5 mg/L, respectively). The lower DO limit is required in order to avoid sludge bulking.

As shown in Figure 8, influent pH value is checked first. Addition of acidic or alkaline wastes is recommended when the pH value is higher than 9, or lower than 6, respectively.

If the pH profile is of a rising type, which suggests the completion of nitrification at the point where the pH bends, the controller tries to reduce aeration to the reactor. If DO concentration in aerobic zones is already at or lower than the lower limit of 0.5 mg/L,

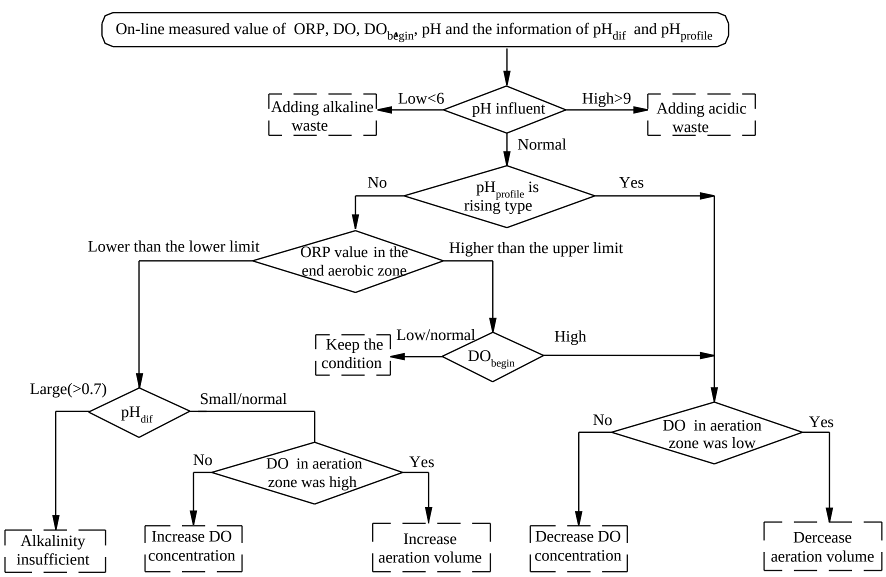

Figure 8 The inference procedure of the proposed fuzzy logic controller

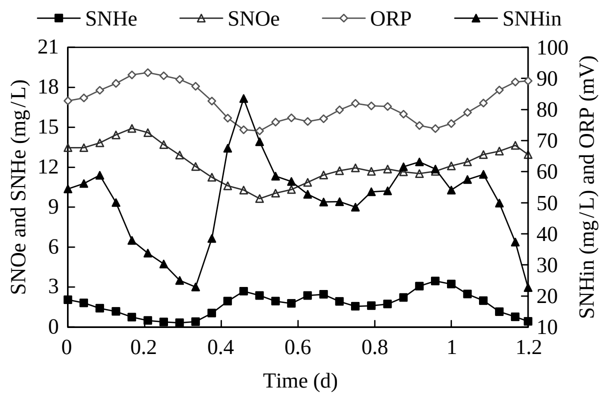

Figure 9 The results of fuzzy inference control

then aeration volume is reduced through switching off aeration to one zone at a time. Otherwise DO level is reduced based on the position of 'ammonia valley' in the aerobic zones.

If the pH profile was of a descending type, nitrification unlikely finished in the zones prior to the last one. If ORP value in the last aerobic zone is higher than the upper limit level of 85 mV, full or near-to-full nitrification likely occurred in the last aerobic zone. In this case, the DO concentration in the first aerobic zone (DO_{begin}) is checked. An increasing DO indicates that a low load is arriving, the aeration needs to be reduced with the procedure discussed in the previous paragraph. Otherwise, no change to the aeration should be made. If an ORP value lower than the lower limit level of 70 mV is observed, full nitrification is not achieved with the causes to be identified. If the pH variation across in the aerobic zones (pH_{dif}) is large (>0.7), the inadequate nitrification could likely be caused by the deficiency of alkalinity, the influent alkalinity should therefore be increased; otherwise, DO in the aerobic zones should be increased or the aeration volume increased by turning on the aeration in a zone currently used as an anoxic zone.

The fuzzy inference system was implemented and demonstrated on the bench-scale reactor system. Fuzzification was performed using the Gaussian membership, and the Mamdani model with max–min operation was used for inference. Defuzzification was performed with a center of area method to generate a final output value. The inference procedure was executed every 20 min.

Promising results were obtained over the 2-week testing period. Figure 9 shows the influent ammonia and effluent ammonia and nitrate concentrations over a 29-h period, along with the ORP in the last aerobic zone. Low effluent ammonia concentration (0.5–3 mg/L) was achieved despite large variations in the influent ammonia concentration. The effluent ammonia concentration and airflow rate were both reduced by about 10%, compared to previous operation.

Conclusions

DO, pH and ORP signals have good potentials to be used for the control of continuous biological wastewater treatment systems:

- Through providing constant aeration to the first aerobic zone in a plug-flow like reactor, the DO level in this zone displayed strong correlation with the nitrogen load to the system, which can be used as feedforward information for aeration control in the remaining part of the reactor. The net change of pH between the first and last aerobic reactors provides similar information and could therefore be used in conjunction with the DO signal.

- With DO in the last aerobic zone controlled at a constant level, the ORP value in this zone has good correlation with the ammonia and nitrate concentrations in this zone, and could therefore potentially be used as an indicator of the latter variables.
- The spatial variation of pH along the reactor gives strong indication of the extent of nitrification. A rising pH towards the end of the reactor suggests complete nitrification, and aeration could be reduced, while a descending pH throughout the reactor suggests incomplete nitrification, which could be improved through increasing aeration or adding alkalinity.
- It is possible to design fuzzy controllers for the control of continuous predenitrification systems using the DO, pH and ORP sensors. A preliminary test showed promising results.

Acknowledgements

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