

## Use of pH as fuzzy control parameter for nitrification under different alkalinity in SBR process

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**Abstract** In order to achieve fuzzy control of nitrification in a Sequencing Batch Reactor (SBR) brewery wastewater was used as the substrate. The effect of alkalinity on pH variation during nitrification was systematically studied, at the same time the variations of DO and ORP were investigated. Alkalinity and pH of the wastewater were adjusted by adding sodium bicarbonate at five levels and sodium hydroxide at two levels. Unadjusted wastewater was also studied. According to the results, variation of pH could be divided into rising type and descending type. When bicarbonate alkalinity was deficient or sufficient, the descending type happened. If alkalinity was deficient, the pH decreasing rate got slower when nitrification nearly stopped; if alkalinity was sufficient, at the end of nitrification pH turned from decrease to increase. This was the most common situation and pH could be used to control the end of nitrification. When alkalinity was excessive, the rising type happened, pH was increasing at nearly a constant rate during and after nitrification and could not be used to control the nitrification time, but if the aeration rate was moderate DO could be used to control the nitrification time. This situation seldom happened. Therefore the variation of pH could not only be used to control the nitrification time but also to judge whether the alkalinity was enough or not. On the basis of this, the fuzzy controller of nitrification in SBR was constructed. When discussing the influence of pH on nitrification rate the composition and concentration of alkalinity must be considered or else the results may be incomprehensive. And to some extent the influence of alkalinity on nitrification rate was more important than pH.

**Keywords** Alkalinity; DO; fuzzy control; nitrification; pH; SBR

### Introduction

As a simple and compact wastewater treatment system, the sequencing batch reactor (SBR) is capable of removing the biological carbon and nutrient by cycling anaerobic, aerobic, anoxic, and by setting and discharging the operation phase. However SBR is usually controlled with a steady-state sequential approach which always leads to tremendous energy and resources consumption owing to the influent fluctuation and system state variations. For cost reduction and process optimization the automatic control of SBR should be realized. The reaction time of the continuous flow reactor is controlled by the influent flux, but the reaction time of SBR could be changed. So the key problem is to control the reaction time of SBR.

Because a large number of kinetic and stoichiometric parameters can't be analyzed on-line, model-based control strategies need a hindrance to be applied. Some researchers placed focus on *in-situ* nutrient sensors (Ingildsen and Olsson, 2002). The commonly used control parameters are ORP (Oxidation-Reduction Potential), DO (Dissolved Oxygen) and pH, as their probes are easy to be used and not expensive. Recently many researchers have demonstrated the efficiency of these parameters both under aerobic and anoxic conditions. For example, at the end of denitrification there is a "nitrate knee" in the ORP profile and a "nitrate apex" in the pH profile (Wareham *et al.*, 1993; Paul *et al.*, 1998; Cho *et al.*, 2001). And through comparing the different increasing rates of pH during denitrification, whether

the carbon is enough or not can be deduced and when the carbon should be added again can be decided (Peng *et al.*, 2002). With regard to nitrification, a number of studies suggested a control method based on a fixed value of ORP (Charpentier *et al.*, 1987; Tomlins *et al.*, 2002), however the ORP values in the same system can be affected by factors such as chemical species, solid concentration, biological activity, pH and temperature. And under aerobic condition DO is more useful than ORP to adjust aeration rate and to control the nitrification time. Because pH values reflect the course of biological nitrogen removal, specifically the degree of nitrification and denitrification, some authors preferred to use the pH variation for nutrient removal (Al-Ghusain and Hao, 1995; Chang and Hao, 1996). Because biological wastewater treatment processes are time-varying, ill defined and non-linear systems, many researchers have applied fuzzy control to them (Tong *et al.*, 1980; Fu and Poch, 1998).

The specific objective of this study was to establish fuzzy control strategies for nitrification in the SBR process. The effect of alkalinity on pH variation during nitrification was systematically studied, at the same time the variations of DO and ORP were observed.

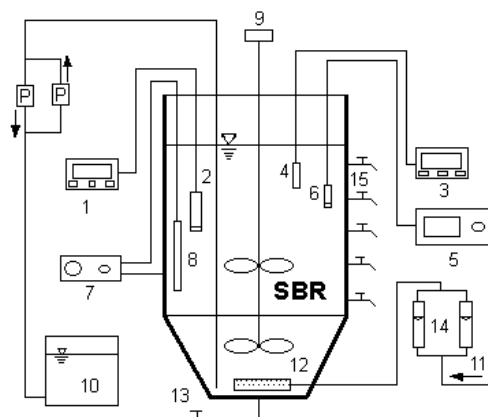
## Materials and methods

### Sludge and wastewater

The seeding sludge for the bench-scale reactor was obtained from a conventional activated sludge process. The feed was mixed beer and tap water. Nitrogen and phosphorus concentrations were adjusted by adding  $\text{NH}_4\text{Cl}$  and  $\text{KH}_2\text{PO}_4$  to the feed water. Sodium bicarbonate or sodium hydroxide was also added to increase alkalinity. After the culture of the activated sludge, the experiments lasted for 7 months.

### Reactor system

A bench-scale reactor was made of a plexiglass pipe (diameter 30 cm, length 70 cm) with a working volume of 38 L (Figure 1). An air compressor was used for aeration. A mechanical mixer was used to assist aeration and provide liquid mixing when the compressor stopped working. The temperature of the reactor was kept at  $30 \pm 1^\circ\text{C}$ . The SBR had six sequences: influent feeding, aerobic reaction, anoxic reaction, re-aeration, sludge settling and effluent decanting. Continuous carbon addition was carried out using an adjustable speed peristaltic



1. ORP meter 2. ORP probe 3. pH meter 4. pH probe 5. DO meter 6. DO probe 7. temperature controller 8. temperature probe 9. mixer 10. sludge tank 11. compressed air 12. diffuser 13. waste sludge 14. air flow meter 15. outlet

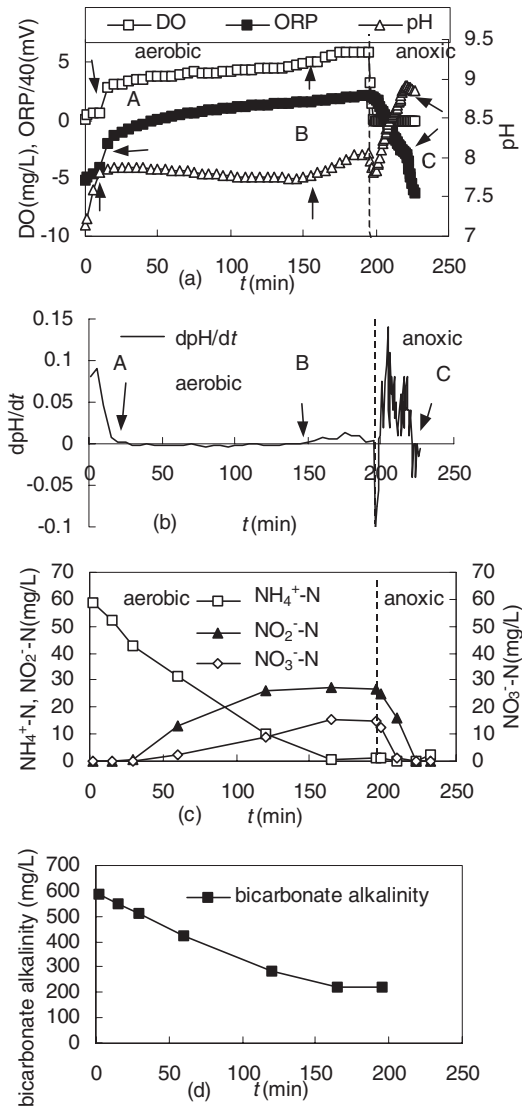
pump (PST-100N, IWAKI, Japan). During the reaction DO, pH and ORP were detected on-line, samples were collected at intervals according to DO, pH and ORP variations.

#### Analytical methods

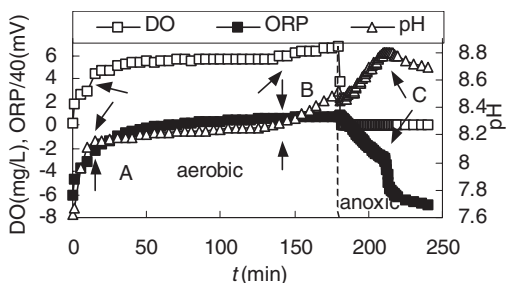
The DO and temperature were measured continuously using a YSI 5730 oxygen probe. Continuous monitoring of pH and ORP were carried out using two PHS-3C meters with an ORP electrode E-414Q and a pH probe E-201.  $\text{COD}_{\text{Cr}}$ , MLSS,  $\text{NO}_2^-$ -N,  $\text{NO}_3^-$ -N,  $\text{NH}_4^+$ -N,  $\text{PO}_4^{3-}$ -P and alkalinity were measured according to *Standard Methods* (APHA, 1995).

#### Experimental procedures

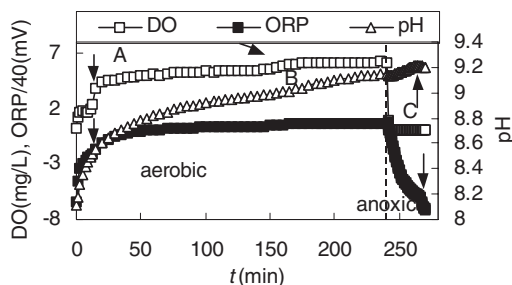
In order to investigate the variations of pH, DO and ORP during nitrification in the SBR process, in all the experiments the aeration rate was maintained at  $0.8 \text{ m}^3/\text{s}$ . The MLSS was



**Figure 2** Track study results of nitrogen removal (initial bicarbonate alkalinity was 586 mg/L); (a): profiles of DO, ORP and pH; (b): dpH/dt profile; (c): dynamics of  $\text{NH}_4^+$ -N,  $\text{NO}_2^-$ -N,  $\text{NO}_3^-$ -N; (d): dynamics of bicarbonate alkalinity during nitrification



**Figure 3** The profiles of DO, ORP and pH of nitrogen removal in SBR process (initial bicarbonate alkalinity was 1,163 mg/L)



**Figure 4** The profiles of DO, ORP and pH of nitrogen removal in SBR process (initial bicarbonate alkalinity was 5,146 mg/L)

maintained at 4,000 mg/L, and at the beginning of the aerobic reaction the COD and ammonia concentrations in the reactor were 300 mg/L and 60 mg/L respectively. The phosphate amounts were maintained at suitable values to avoid influence on the pH variation. Alkalinity and pH of the wastewater were adjusted by adding sodium bicarbonate at five levels and sodium hydroxide at two levels. Unadjusted wastewater was also studied.

Under the last two conditions the bicarbonate alkalinity was not enough for nitrification, and in order to make the experiments comparative, after each cycle the liquid left in the reactor was washed with tap water to remove the residual ammonia. Each level experiment was conducted for 15~20 cycles and then taken to the track study.

## Results and discussion

### Wastewater alkalinity and pH were adjusted by adding sodium bicarbonate

The initial concentrations of bicarbonate alkalinity of these experiments were 586 mg/L, 1,163 mg/L, 1,707 mg/L, 3,163 mg/L and 5,146 mg/L respectively (calculated by  $\text{CaCO}_3$ ). With respect to the initial ammonia concentration (60 mg/L), if the ammonia that the COD removal needed was not considered, the initial bicarbonate alkalinities of these experiments were 1.37, 2.74, 4.03, 7.46 and 12.1 times that needed.

*Initial bicarbonate alkalinity concentration was 586 mg/L.* The bicarbonate alkalinity was 1.37 times that needed. The track study results are shown in Figure 2. During the COD removal, pH increased quickly. When nitrification began, pH turned from increase to decrease (Figure 2(a), point A). At the end of nitrification, pH increased sharply (Figure 2(a), point B). This point could be used to control the nitrification time. At the end of denitrification, the “nitrate apex” (Figure 2(a), point C) appeared in the pH curve which indicated the end of denitrification.

The derivative of pH also showed the same significant points (Figure 2(b)). At the end of

COD removal,  $\text{dpH}/\text{dt}$  turned from positive to negative; at the end of nitrification,  $\text{dpH}/\text{dt}$  turned from negative to positive and at the end of denitrification,  $\text{dpH}/\text{dt}$  turned from positive to negative. These significant points could be used to control the reaction time of carbon and nitrogen removal in the SBR process.

The variation of pH was the results of stripping of  $\text{CO}_2$  and the consuming of bicarbonate alkalinity by nitrification. When the bicarbonate alkalinity was sufficient but not in excess (1.37 times that needed), nitrification consuming alkalinity was dominant, during nitrification pH decreased; but at the end of nitrification, stripping of  $\text{CO}_2$  was dominant, pH turned from decrease to increase, which indicated the end of nitrification. This was the most common situation.

During the COD removal, DO showed a platform and ORP increased slowly. This was because the OUR was nearly constant. When the removal of COD had nearly stopped (Figure 2(a), point A), because the oxygen supplied was higher than the oxygen consumed under constant aeration rate, DO and ORP both increased sharply. During nitrification, DO and ORP increased slowly, at the end of nitrification, DO increased quickly (Figure 2(a), point B) and ORP showed a platform; this characteristic could be used to control the nitrification time. At the end of denitrification, the “nitrate knee” appeared in the ORP curve. ORP and pH are useful during the aerobic and anoxic phases, but DO is only useful under the aerobic phase. Comparing with the dynamics of ammonia and the bicarbonate alkalinity (Figure 2(c) and (d)) shows that when the bicarbonate alkalinity was sufficient but not in excess DO and pH could be used together to control the nitrification time.

*Concentrations of initial bicarbonate alkalinity were 1,163 mg/L, 1,707 mg/L, 3,163 mg/L and 5,146 mg/L.* Under these conditions at the end of COD removal and denitrification, pH, DO and ORP showed the same characteristics and at the end of nitrification ORP got to a platform. Figure 3 shows the results that initial bicarbonate alkalinity was 1,163 mg/L. During nitrification pH did not decrease but increased slowly,  $\text{dpH}/\text{dt}$  was maintained at  $0.001 \text{ min}^{-1}$ ; and the increasing rate became fast at the end of nitrification (140 min),  $\text{dpH}/\text{dt}$  was maintained at  $0.006 \text{ min}^{-1}$ , which was six times the value during nitrification. The different increasing rate of pH could be used to control the end of nitrification. And during nitrification  $\text{dDO}/\text{dt}$  was maintained at  $0 \text{ mg/L}/\text{min}$ , DO increased quickly at 140 min,  $\text{dDO}/\text{dt}$  was maintained at  $0.02\sim 0.046 \text{ mg/L}/\text{min}$ . Under this condition DO and pH could still be used to control the nitrification time.

When the concentrations of initial bicarbonate alkalinity were 1,707 mg/L and 3,163 mg/L, the profiles of DO, ORP and pH were similar to the profiles when the initial bicarbonate alkalinity was 1,163 mg/L. The only difference was that the significant points of pH and DO appeared a little earlier before the end of nitrification and the difference between the pH increasing rate was smaller.

Figure 4 shows the results that initial bicarbonate alkalinity was 5,146 mg/L. With the initial bicarbonate alkalinity increased (2.74, 4.03 and 7.46 times that needed), during nitrification the stripping of  $\text{CO}_2$  gradually became dominant, pH did not decrease, it increased from slowly to fast, but at the end of nitrification, the pH increasing rate was faster than the rate during nitrification, and pH still could be used to indicate the end of nitrification. But when the initial bicarbonate alkalinity increased to 12.1 times that needed, stripping of  $\text{CO}_2$  was absolutely dominant, so pH increased at nearly a constant speed during and after nitrification. Under this condition pH could not be used to control the nitrification time, this situation seldom happened. But Figure 4 shows that DO increased quickly from 150 min, so if the aeration rate was moderate, DO could be used to control the end of nitrification. And DO will be invalid too if the aeration rate is too high.

### Wastewater alkalinity and pH were not adjusted

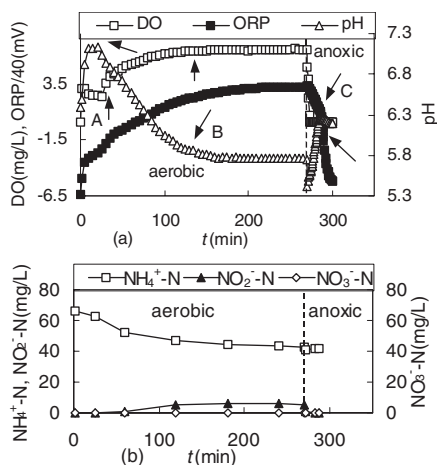
The results are shown in Figure 5. Figure 5(a) shows how during nitrification pH decreased from the beginning of nitrification to 120 min,  $dpH/dt$  was maintained at  $-0.010 \text{ min}^{-1}$ ; and then the decreasing rate became slow and  $dpH/dt$  was between  $-0.003 \sim 0 \text{ min}^{-1}$ . During nitrification the range of pH was 5.75~7.13. Figure 5(b) shows that after 120 min nitrification nearly stopped. Under this condition, because the bicarbonate alkalinity was not enough, nitrification consuming alkalinity was dominant and nitrification led the pH to be too low, the nitrification rate was small and nitrification did not complete. So at the beginning of nitrification pH decreased quickly and near the stopping of nitrification the pH decreasing rate became slow. The difference of pH decreasing rate could be used to indicate the stopping of nitrification and also indicate that the alkalinity was not enough and another amount of bicarbonate alkalinity should be added to make the nitrification complete.

Figure 5 also shows that during nitrification DO increased incessantly, when nitrification nearly stopped, DO did not increase quickly but showed a platform near the saturated value. This was because the pH was too low, which made the bacteria respiration rate low and the rate of oxygen supplied was nearly equal to the rate of oxygen consumed. The platform of DO could be used to indicate the stopping of nitrification. Under this condition, the significant points of pH and DO were delayed for some time, though this was not beneficial to conventional automatic control, it was suitable for fuzzy control.

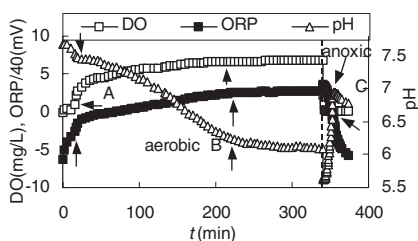
### Wastewater alkalinity and pH were adjusted by sodium hydroxide

At the beginning of the aerobic phase the pH in the reactor was 7.68 and 9.01 respectively. The results are shown in Figures 6 and 7. Figure 6 shows that the variations of pH, DO and ORP were similar to the situation in which wastewater alkalinity and pH were not adjusted. The only difference was that during COD removal pH did not increase but decreased.

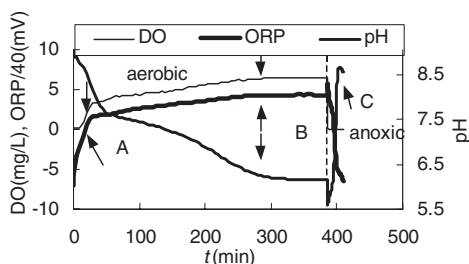
In order to make the bicarbonate alkalinity enough, the dosage of sodium hydroxide was increased. Though at the beginning of the second level experiment pH was 9.01 the



**Figure 5** Track study results (without adjusting alkalinity) (a): the profiles of DO, ORP and pH; (b): dynamics of  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_2^-\text{-N}$ ,  $\text{NO}_3^-\text{-N}$



**Figure 6** The profiles of DO, ORP and pH of nitrogen removal in SBR process (initial pH was 7.68)



**Figure 7** The profiles of DO, ORP and pH of nitrogen removal in SBR process (initial pH was 9.01)

bicarbonate alkalinity was still not enough. Figure 7 shows that the variations of pH, DO and ORP were similar to the situation in which initial pH was 7.68.

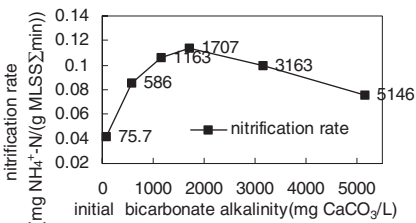
According to the results, variation of pH could be divided into rising type and descending type. When alkalinity was deficient or sufficient, the descending type happened and pH could be used to control the time of nitrification; when alkalinity was excessive, the rising type happened and DO could be used to control the reaction time of nitrification. pH could be used to control the nitrification time and indicate whether the alkalinity was enough or not. DO is the sign of energy consumed and could be used to control the aeration rate and nitrification time. DO and pH could be used together to control the nitrification time, aeration rate and alkalinity.

**Fuzzy control rules of nitrification in SBR**

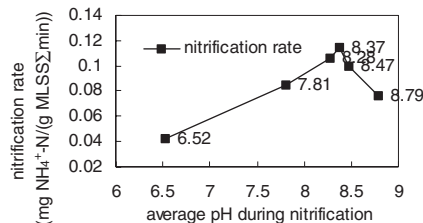
Building an on-line fuzzy controller is the kernel of fuzzy control theory, and the fuzzy control rules are the heart of the fuzzy controller. On the basis of collecting and analyzing all useful historical data, two input variables for the fuzzy controller were selected, such as  $dpH/dt$  ( $CE_{pH}$ , the first derivative of the pH profile) and  $T_{pH}$  (duration from the point that pH decreasing rate became slow to the stopping of nitrification). There was one output variable, aeration rate ( $U_A$ ). The fuzzy controller includes data fuzzification, determining membership functions for all the linguistic variables, establishing the fuzzy control rules and defuzzification of output data. With respect to controlling the time of nitrification, when bicarbonate alkalinity was sufficient but not in excess, IF  $CE_{pH}$  turned from N(Negative) to P(Positive) THEN stopping aeration. (“IF...THEN...” is the linguistic expression that is commonly used in fuzzy control); when bicarbonate alkalinity was insufficient, IF  $CE_{pH}$  turned from N to O (zerO) and  $E_T$  was at PB (Positive Big) THEN stopping aeration. The details of using pH and DO as fuzzy control parameters for aeration rate and nitrification time are discussed in another paper (Gao, 2001).

**Relationships between pH, alkalinity and nitrification rate**

Figures 8 and 9 present the influence of pH and bicarbonate alkalinity on the nitrification rate. It shows that when the average pH during nitrification was 8.37 (the initial bicarbonate alkalinity was 1,707 mg/L) the nitrification rate was the biggest. To the wastewater used here, it was more useful in nitrification to use sodium bicarbonate to adjust the alkalinity and pH than using sodium hydroxide. But if the pH of the wastewater is below 4, it should first be adjusted by sodium hydroxide and then by sodium bicarbonate or sodium carbonate. If the bicarbonate alkalinity is enough, the efficiency of ammonia removal was more than 98% and the influence of pH on nitrification rate was small. When discussing the influence of pH on nitrification rate the composition and concentration of alkalinity must be considered or else the results may not be comprehensive.



**Figure 8** Effect of bicarbonate alkalinity on nitrification rate



**Figure 9** Effect of pH on nitrification rate (bicarbonate alkalinity was sufficient)

## Conclusions

According to the results, variation of pH could be divided into rising type and descending type. When alkalinity was deficient or sufficient, the descending type happened and pH could be used to control the time of nitrification; when alkalinity was excessive, the rising type happened and DO could be used to control the reaction time of nitrification.

pH could be used to control the nitrification time and indicate that the alkalinity was enough or not. DO could be used to control both the aeration rate and nitrification time. It was reliable to use pH and DO as fuzzy control parameters of nitrification in SBR.

It was shown when the average pH during nitrification was 8.37 that the nitrification rate was the biggest. When discussing the influence of pH on nitrification rate the composition and concentration of alkalinity must be considered or else the results may not be comprehensive. To some extent the influence of alkalinity on nitrification rate was more important than pH.

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