



## Real-time control of oxic phase using pH (mV)-time profile in swine wastewater treatment

C.H. Ga, C.S. Ra\*

Department of Animal Life System, Kangwon National University, Hyoja 2, 192-1, Chunchon 200-701, South Korea

### ARTICLE INFO

#### Article history:

Received 25 February 2009  
Received in revised form 24 June 2009  
Accepted 24 June 2009  
Available online 2 July 2009

#### Keywords:

Swine wastewater  
Real-time control  
Moving slope change (MSC)  
Oxidation–reduction potential (ORP)  
pH (mV)

### ABSTRACT

The feasibility of real-time control of the oxic phase using the pH (mV)-time profile in a sequencing batch reactor for swine wastewater treatment was evaluated, and the characteristics of the novel real-time control strategies were analyzed in two different concentrated wastewaters. The nitrogen break point (NBP) on the moving slope change (MSC) of the pH (mV) was designated as a real-time control point, and a pilot-scale sequencing batch reactor (18 m<sup>3</sup>) was designed to fulfill the objectives of the study. Successful real-time control using the developed control strategy was achieved despite the large variations in the influent strength and the loading rate per cycle. Indeed, complete and consistent removal of NH<sub>4</sub>-N (100% removal) was achieved. There was a strong positive correlation ( $r^2 = 0.9789$ ) between the loading rate and soluble total organic carbon (TOCs) removal, and a loading rate of 100 g/m<sup>3</sup>/cycle was found to be optimum for TOCs removal. Experimental data showed that the real-time control strategy using the MSC of the pH (mV)-time profile could be utilized successfully for the removal of nitrogen from swine wastewater. Furthermore, the pH (mV) was a more reliable real-time control parameter than the oxidation–reduction potential (ORP) for the control of the oxic phase. However, the nitrate knee point (NKP) appeared more consistently upon the completion of denitrification on the ORP-time profile than on the pH (mV)-time profile.

© 2009 Elsevier B.V. All rights reserved.

### 1. Introduction

Discovering an efficient way to treat swine wastewater is of great concern all over the world as the growth of the animal industry has inevitably resulted in pollution problems due to animal wastes. The main problems are malodor and water pollution. Animal wastes contain large amounts of nutrients, including nitrogen, phosphorus, potassium and various other minerals, which can cause water pollution. At the same time, a number of gaseous substances that cause serious environmental problems are contained in animal wastes. Among these, ammonia, methyl-mercaptan and hydrogen sulfides are the most notable [1].

Animal wastes can be converted into valuable fertilizer and environmentally friendly liquid fertilizer for crop production through anaerobic and aerobic digestion processes. As far as swine wastewater treatment is concerned, anaerobic digestion is an important alternative to land application because it reduces pollution and recovers methane [2]. Indeed, anaerobic digestion has been widely applied to piggery waste treatment [3–7], and anaerobic sludge treatment of piggery wastewater has been successfully used to carry out the denitrification process [8]. However, advanced treat-

ment processes using biological, chemical and physical methods should follow anaerobic digestion and further treat the liquor before discharge. Wang et al. [9] treated wastewater using micro-filtration and ultra-filtration methods. While these processes produce acceptable results, they are expensive and have some obvious disadvantages, such as the use of large areas of land, complicated operations and sophisticated management requirements. Therefore, it is important to develop efficient and economical treatment processes that can completely remove the pollutants from animal wastewater.

It is important to note that since the characteristics of the animal wastewaters discharged from farms are very variable, the fixed hydraulic retention time (HRT) used in traditional treatment processes frequently results in poor control over the quality of the effluent and in extended treatment that is inefficient in terms of energy consumption [10]. Therefore, a novel treatment technology that can treat animal wastewaters efficiently in spite of the serious variation of influent and can optimize electrical energy usage should be established.

Real-time control is believed to be useful in optimizing the energy requirements of biological treatment processes, because aeration and mixing are ceased as soon as the targeted compound is treated [10]. During the last decade, many researchers have considered the oxidation–reduction potential (ORP), the pH, the dissolved oxygen (DO) levels, and the oxygen uptake rate (OUR) for monitor-

\* Corresponding author. Tel.: +82 33 250 8618; fax: +82 33 251 7719.  
E-mail address: [changsix@kangwon.ac.kr](mailto:changsix@kangwon.ac.kr) (C.S. Ra).

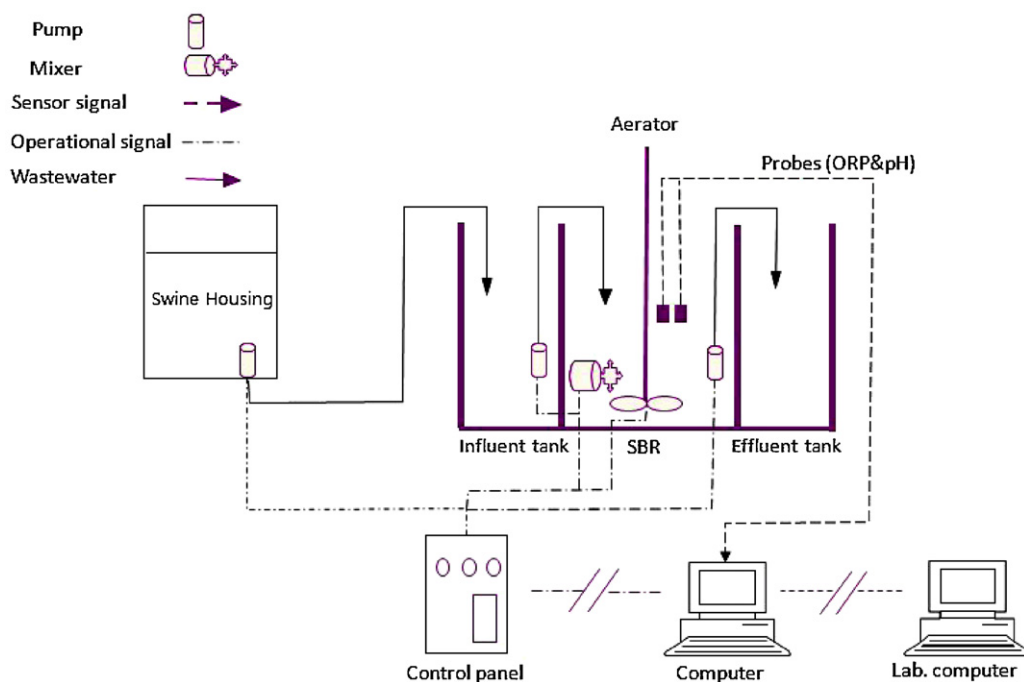


Fig. 1. Schematic process with on-line control system.

ing and controlling the biological nutrient removal process. The ORP and DO levels can successfully indicate the oxidative and biological state of the wastewater, and pH is a good indicator of ongoing biological reactions. Additionally, OUR signals can efficiently indicate the end point of nitrification and denitrification reactions [1,11–17]. Several researchers [1,3,10,16,18,19] studied nutrient removal from animal wastewater using a sequencing batch reactor (SBR) and a real-time control strategy that included considerations of the ORP and pH. We have recommended that the mV value of pH be used for the detection of control points, not the unit-pH values in 1998 [1]. Since the unit-pH change at real-time control point is usually kept within a 0.2 unit value for over more than 1 h, the use of the unit value can sometimes make it difficult to detect significant slope change at the control point. However, the real-time control point on the pH profile can be identified readily by using the  $d(\text{mV})/\text{pH}/dt$ , since the mV-pH values have a large-scale slope change at the control point. Usually, 1 unit pH change has approximately 60 mV-pH variation, depending upon the pH electrolyte. In this study, we designed a pilot-scale SBR and evaluated the feasibility of the developed real-time control strategy of the aerobic treatment duration using pH (mV)-time profile in different concentrations of swine wastewater. Furthermore, the operational characteristics of the real-time control process were analyzed.

## 2. Materials and methods

### 2.1. System configuration and process operation

A schematic diagram of the SBR system is shown in Fig. 1. The working volumes of the influent storage tank, the SBR, and the effluent storage tank were 6, 18, and 6 m<sup>3</sup>, respectively, and the total volume of the SBR was 24.2 m<sup>3</sup> (380 cm × 300 cm × 230 cm). A submersible aerator (KS, Inc.) and a mixer (KH, Inc.) were set at the bottom of the reactor to ensure aeration and complete mixing. To achieve real-time control and to monitor biological status, ORP and pH probes were inserted into the reactor and connected to a custom-built amplifier for the accurate measurement of voltage. Electrical signals obtained from the reactor were relayed into a

computer through an electric cable ribbon, and the computer was connected to the Internet. Swine wastewater was stored in the influent tank after solid/liquid separation using gravity. The SBR process was operated with the sequence presented in Table 1. After the swine wastewater was fed into the reactor, it was kept in anoxic conditions for 12 h before the air was turned on. The duration of the oxic phase was determined by the real-time control system. Upon the detection of the nitrogen break point (NBP) on the pH (mV)-time profile, aeration was stopped. The sludge was then settled and the effluent was discharged. Two runs of real-time control operations were performed using this system. The operational conditions for Runs I and II were identical, except influent strength. To test stability of the real-time control strategy under a variable loading rate condition, much low strength influent relatively to Run I was used in Run II. The volume of influent loaded into the system was 1 m<sup>3</sup>/cycle and sludge wastage for SRT control was not conducted during operation to test the feasibility of the designed real-time control strategy under a variable biological status. During the operations, the levels of MLSS and MLVSS were in the range of 4.44–8.64 mg/L (average 5.81 mg/L) and 4.34–6.66 mg/L (average 5.07 mg/L), respectively. Also, the air temperature recorded during the experimental period was average 12 °C.

### 2.2. Real-time and remote control strategies

The process placed on animal farm was monitored and controlled through the Internet from the university laboratory located 25 km from the farm. When trouble occurred, the process was corrected by remote control. A layout of the real-time control strategy is shown in Fig. 2. After feeding the swine wastewater into the SBR, the computerized program took readings from the reactor of the ORP and pH (mV) values every second and calculated an average

Table 1  
Operation modes for SBR.

Sequences	Feeding	Anoxic	Aerobic	Settle	Discharge
Duration (h)	0.33	12	Real-time control	2	0.33

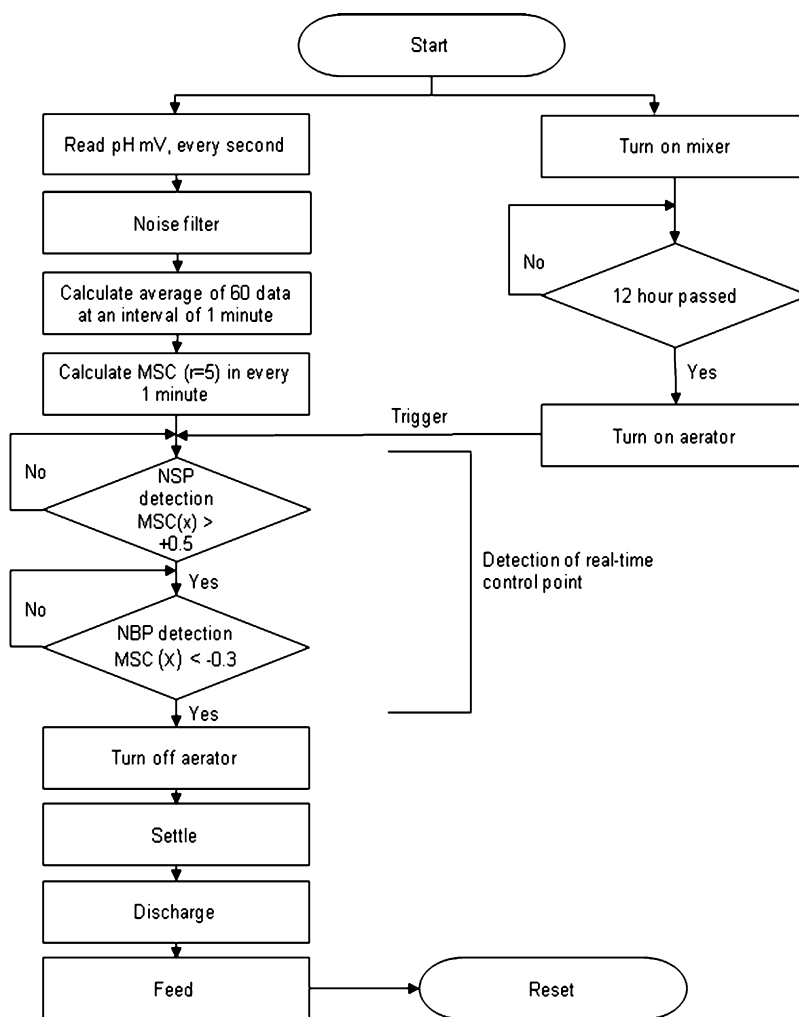


Fig. 2. Control strategy of the process using pH (mV)-time profile.

of 60 data points every minute. The average ORP and pH (mV) values were logged for the monitoring of profiles and further signal processing. The moving slope change (MSC) of the pH (mV) value was calculated every minute, with a data sample size of five values. The detailed calculations of the MSC ( $r=5$ ) are shown in Fig. 3. In the figure,  $N_n$  is the block average value of the temporary storage of the 60 data points inputted every second, while  $X_n$  is the MSC calculated each minute ( $r=5$ ). For the calculation of the MSC, the computer program looked back at the five most recent block average values ( $N_n$ ) logged each minute, and the difference ( $X_n$ ) between the oldest and newest values was calculated every minute. When the next value was recorded, the oldest point was dropped and the MSC was calculated again. The real-time control point (RTCP) was detected by tracking the change pattern of the MSC and was pro-

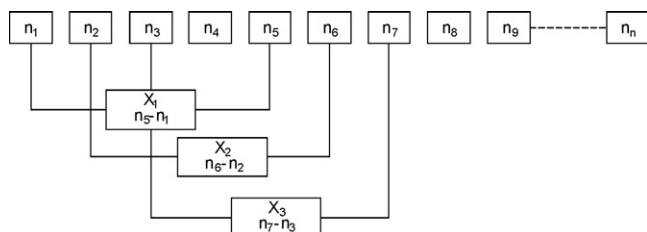


Fig. 3. Calculation procedure of moving slope change (MSC).  $X_n$ : MSC value calculated in every minute ( $r=5$ ).  $N_n$ : block average value (60 data point).

grammed to be triggered after the process was in anoxic conditions for 12 h.

To prevent an erroneous process control, the control strategy was programmed to recognize each feature in sequence (Fig. 4). For the real-time control of the process, the NBP was detected in sequence after recognizing the nitrification starting point (NSP). With this strategy, real-time control of the oxic phase began at the onset of the NBP on the MSC-time profile. More than +0.5 and less than -0.3 of the MSC were used as the trigger value to recognize the NSP and NBP, respectively. At the onset of the NBP on the MSC- and pH (mV)-time profiles (Fig. 4b), aeration was terminated and the whole procedure was reset for the next cycle, which began after the sludge was settled, the effluent was discharged, and the influent was fed into the reactor. The tracking of  $\text{NH}_4\text{-N}$  and  $\text{NO}_x\text{-N}$  levels (Fig. 4a) shows that the designated NSP is the beginning of nitrification, while the designated NBP is the completion point of nitrification.

### 2.3. Analytical methods

Influent and effluent samples were collected and preserved at 4 °C until analysis. Solid analyses were performed immediately after sampling and other chemical contents were measured within one week. The parameters studied were soluble total organic carbon (TOCs), ammonium nitrogen ( $\text{NH}_4\text{-N}$ ), nitrate and nitrite nitrogen ( $\text{NO}_x\text{-N}$ ), orthophosphate ( $\text{PO}_4^{3-}$ ), total solids (TS), total volatile

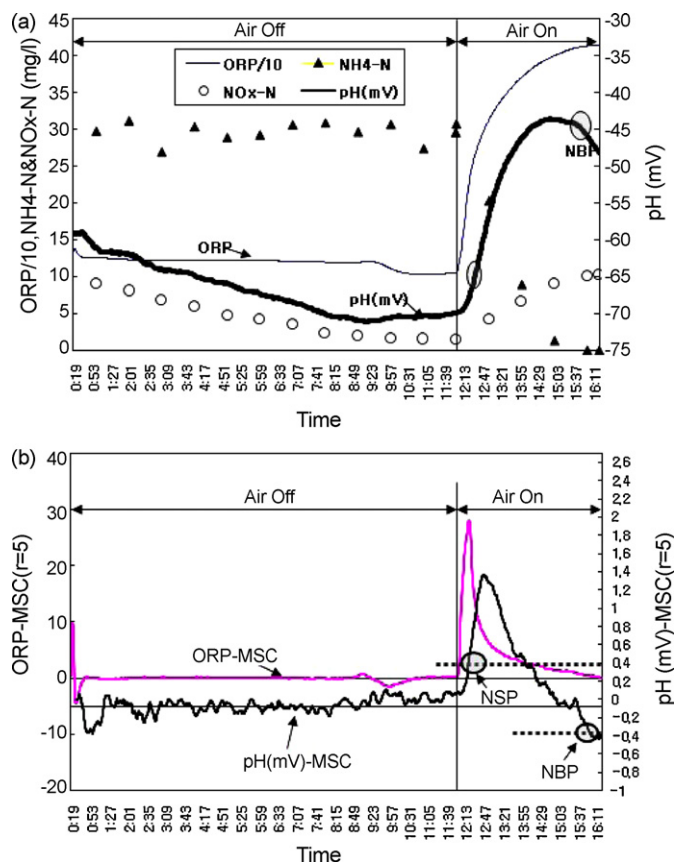


Fig. 4. Profiles of ORP and pH mV (a) and MSC (b).

solids (TVS), suspended solids (SS) and volatile suspended solids (VSS). Analyses were performed in accordance with the standard methods [20]. The TOC was analyzed with a Shimadzu total organic carbon analyzer (Model TOC-500), while  $\text{NH}_4\text{-N}$ ,  $\text{NO}_x\text{-N}$ , and  $\text{PO}_4^{3-}$  were analyzed with an auto analyzer (Quick Chem 8000, LACHAT).

### 3. Results and discussion

Fig. 4 shows the changes of  $\text{NH}_4\text{-N}$  and  $\text{NO}_x\text{-N}$  with the ORP and pH (mV)-time profiles under the provided operation condition (Fig. 4a), as well as patterns of MSC of parameters (Fig. 4b). There was a decreasing trend in the pH (mV)-time profile as  $\text{NO}_x\text{-N}$  levels decreased during the 12-h air-off condition, but the ORP profile had no such tendency. The decrease in the pH (mV) profile is likely due to the recovery of alkalinity by the denitrification of  $\text{NO}_x\text{-N}$  in the anoxic phase. With respect to the ORP profile pattern, three types of profile were generally observed in the anoxic condition: (1) no change in the ORP value (constant profile pattern), as in Fig. 4a. In spite of denitrification during the anoxic phase, no changes in the ORP were observed; (2) A slight increase or decrease, as shown in Fig. 5a. During the denitrification of  $\text{NO}_x\text{-N}$ , the ORP values slowly increased or decreased. The features described in (1) and (2) may mean that the ORP values are not directly related to  $\text{NO}_x\text{-N}$  levels in the reactor; (3) An abrupt drop. The ORP value suddenly dropped very low during the anoxic phase, as shown in Fig. 5b. In the figure, this point was expressed as the nitrate knee point (NKP) and surely indicates the time when the denitrification of  $\text{NO}_x\text{-N}$  was completed in the reactor [10,21].

Upon beginning aeration, nitrification of  $\text{NH}_4\text{-N}$  occurred and increased the ORP and pH (mV)-time profiles. This increase in the ORP and pH (mV) values appears to correspond to the provision of air and the nitrification of  $\text{NH}_4\text{-N}$ , respectively (Fig. 4). During

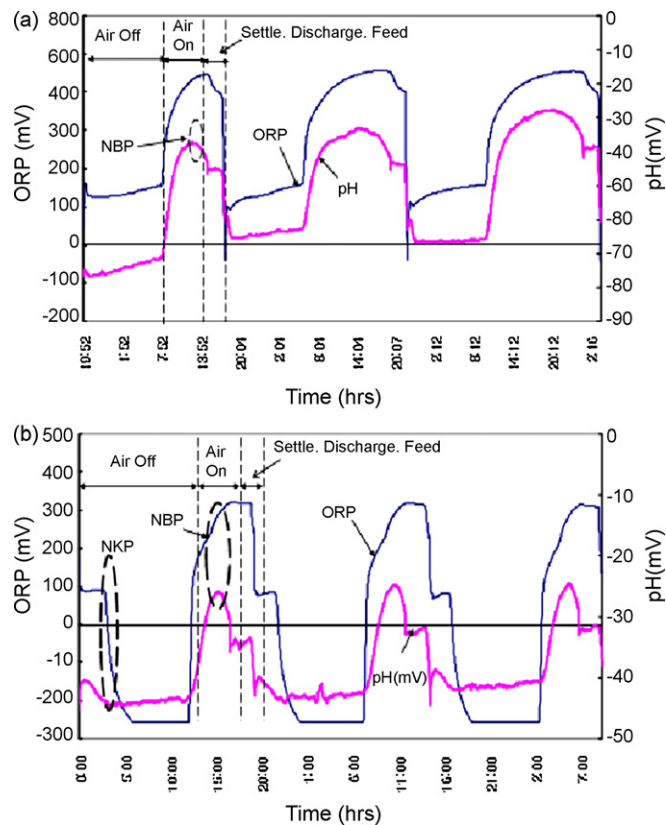


Fig. 5. Operational mode and ORP/pH (mV)-time profile.

nitrification, alkalinity was consumed; this can be inferred by the increase in pH (mV) values. Also, the achieved  $\text{NH}_4\text{-N}$  decrease in the reactor could be due to the occurrence of simultaneous nitrification and denitrification (SND) and ammonia air-stripping. SND can occur within microbial flocs as a result of DO gradients due to air diffusion limitations. It is possible for some denitrifiers to continue denitrifying after increase in DO concentration [22], and it is known that denitrification process is not significantly affected with DO concentration up to 0.6 mg/L [23]. The aeration starting point (ASP), or NSP can be easily detected by monitoring the MSCs of the ORP and pH (mV) values spiked in the air-on condition and then began to decrease during the oxic phase. This ASP (or NSP) on the MSC-pH (mV) was consistently and stably recognized by designating +0.5 for threshold value. As nitrification progressed, the ORP and pH (mV) profile continued to increase. When nitrification was complete, the pH (mV) profile started to decrease and this NBP was recognized by monitoring the MSC-pH (mV)-time profile. The value of the MSC-pH (mV) dropped into the negative range at the end of nitrification, and this NBP was consistently recognized by designating -0.3. On the other hand, such an NBP was not found on the ORP-time profile in many cases (as shown in Figs. 4a and 5a), and the completion point of nitrification could not be recognized by monitoring the MSC of the ORP. The variation in the loading rate, which was due to the influent strength fluctuation and the imbalance between the aeration rate and the oxygen uptake rate (OUR), frequently resulted in the appearance of a false NBP or the disappearance of the NBP on the ORP-time profile. In ideal conditions, however, the ORP profile abruptly increased at the end of nitrification, as is shown in Fig. 5b.

Fig. 5 also shows the ORP- and pH (mV)-time profiles monitored during the operation. Real-time control of the aerobic duration was possible using the programmed control algorithm. As can be seen in the graphs, aeration began after the 12-h anoxic phase and ter-

**Table 2**  
Characteristics of wastewater and removal efficiencies.

Parameter (mg/L)	Run I		Run II			AVG			
	Influent (mean $\pm$ SD <sup>a</sup> )	Effluent (mean $\pm$ SD)	Removal (%)	Influent (mean $\pm$ SD)	Effluent (mean $\pm$ SD)	Removal (%)	Influent	Effluent	Removal (%)
TOCs	1453.9 $\pm$ 533.2	283.4 $\pm$ 50.0	80.5	643.3 $\pm$ 650.3	112.7 $\pm$ 32.8	82.5	1048.6	198.0	81.1
NH <sub>4</sub> -N	1414.6 $\pm$ 231.3	0.0 $\pm$ 0.0	100	480.7 $\pm$ 306.1	0.0 $\pm$ 0.0	100	947.7	0.0	100
NO <sub>x</sub> -N	0.2 $\pm$ 0.4	22.9 $\pm$ 10.9	–	0.4 $\pm$ 0.5	7.8 $\pm$ 8.4	–	0.3	15.5	–
PO <sub>4</sub> <sup>3-</sup> -P	19.1 $\pm$ 8.2	24.2 $\pm$ 2.9	–26.6	18.4 $\pm$ 5.4	14.2 $\pm$ 2.3	22.6	18.7	19.2	–2.5
TS (g/L)	4.16 $\pm$ 0.69	3.19 $\pm$ 0.18	23.2	2.40 $\pm$ 1.68	1.86 $\pm$ 1.17	22.2	3.28	2.23	32.0
TVS (g/L)	1.93 $\pm$ 0.43	0.75 $\pm$ 0.09	61.3	1.22 $\pm$ 0.93	0.74 $\pm$ 0.86	38.8	1.58	0.75	52.5
SS (g/L)	0.40 $\pm$ 0.09	0.22 $\pm$ 0.06	44.4	0.59 $\pm$ 0.52	0.74 $\pm$ 1.43	–24.4	0.50	0.48	4
VSS (g/L)	0.30 $\pm$ 0.08	0.12 $\pm$ 0.02	59	0.49 $\pm$ 0.45	0.54 $\pm$ 1.04	–10.9	0.40	0.33	17.5

<sup>a</sup> SD, standard deviation.

minated when the NBP occurred on the pH (mV)-time profile. This means that the duration of the oxic phase was flexible from cycle to cycle, responding to the physical and biological conditions of the reactor. Even in cases when the NBP did not occur on the ORP-time profile, the pH (mV)-time profile consistently revealed the NBP, and successful real-time control was consequently achieved (Fig. 5a). If the ORP-time profile was used for real-time control of the oxic phase, failure of the process control would have resulted during the operation.

In contrast with observations in Fig. 5a, a clear NBP was observed on both the ORP and pH (mV)-time profiles in the aerobic condition in Fig. 5b. Additionally, the NKP, which indicates the completion of the denitrification process, was observed on both the ORP- and pH (mV)-time profiles during the air-off condition. However, in most cases, the NKP was not clearly observed on the pH (mV)-time profile. The occurrences of the NBP and NKP during operation reflect that ideal conditions were maintained and that the nitrification and denitrification processes were completed, resulting in enhanced nitrogen removal. Several researchers explain the changing patterns in the ORP and pH profiles when the nitrification and denitrification processes are completed in the aerobic and anoxic phases [1,3,10,21,24].

Dissolved oxygen (DO) level in the reactor was usually less than 0.5 mg/L until the occurrence of NBP in oxic phase, but the level was used to jump up to over 4 mg/L at the time of NBP appearance.

Table 2 shows the influent and final effluent characteristics, as well as the treatment efficiencies. The average TOCs concentration and soluble inorganic nitrogen (NH<sub>4</sub>-N + NO<sub>x</sub>-N) in the influent was 1048 and 948 mg/L, respectively, showing an average C/N ratio (TOC/soluble N) of 1.1. The relatively low C/N ratio might indicate that the concentration of organic matter was insufficient for biological nitrogen removal. The strengths of C and N were approximately double in Run I, but other pollutants and the C/N ratios in Runs I and II were similar.

The average removal efficiencies with regard to the TOCs and NH<sub>4</sub>-N were 81 and 100%, respectively. This indicates that complete nitrification always occurred in the reactor and the real-time control strategy worked very efficiently during operations, despite the considerable differences in the influent strengths between Runs I and II; the average concentrations of influent TOCs and NH<sub>4</sub>-N in Run I were 2 and 3 times higher than those in Run II, respectively.

Phosphate removal was inefficient and unstable in this study, obtaining negative and 23% in Runs I and II, respectively. This phosphate removal trait might be due to an insufficient source of readily biodegradable carbon, incomplete denitrification during the anoxic reaction, or solid removal trends. Since insufficient organic matter existed in the influent, and hence the denitrification of NO<sub>x</sub>-N was incomplete during the 12-h anoxic phase, phosphate release would not have occurred. This would result in a low P uptake in the subsequent cycle. An easily biodegradable carbon source is necessary for

proper phosphorus removal during the P release stage in the reactor [25], and the presence of NO<sub>x</sub>-N in the anaerobic condition reduces the amount of phosphorus removed [1,26]. Phosphate removal was also influenced by the C/N ratio of the influent wastewater. An average of 96% of the phosphate was removed when the C/N ratio was 4.47 [5]. Additionally, this solid removal trait should also affect P removal. As shown in Table 2, there was a distinct variation in solid removal efficiency between the two runs. In Run I, comparatively higher levels of TVS, SS, and VSS were removed. On the other hand, in Run II, SS and VSS removals were negative, and this was due to the sludge wash-out during the final effluent decanting phase. Since biological phosphorus removal is ultimately achieved by the wasting of sludge, no P removal occurred in Run I. Because the sludge washed out during the final effluent discharge and sludge wasting for the control of the SRT did not conducted on this run, autolysis of bacteria might have taken place in the reactor, resulting in increased levels of PO<sub>4</sub><sup>3-</sup> in the effluent (negative treatment). On the other hand, the sludge wash-out in Run II may have resulted in the removal of phosphate. For reference, a post-treatment process would be involved for the removal of solids and phosphorus from the effluent before discharging into the environment.

Since the loading rate also affects the removal of organic compounds from swine wastewater, the TOCs and nitrogen removal patterns, along with the loading rate, are illustrated in Fig. 6. There was a high positive correlation ( $r^2 = 0.98$ ) between the loading rate and TOCs removal. As the loading rate increased, more TOCs were removed. However, the percentage removal efficiency remained constant at a loading rate of over 100 g/m<sup>3</sup>/cycle (Fig. 6a). Considering the removal efficiency and the level of TOCs in the final effluent, a loading rate of 100 g/m<sup>3</sup>/cycle could be considered optimum for TOCs removal.

Fig. 6 also shows the nitrogen removal observed during the operation. Despite of variations in the influent strength and the loading rate, NH<sub>4</sub>-N was completely removed (Fig. 6b). This constant and complete removal of NH<sub>4</sub>-N was surely due to the real-time control of the oxic phase using the NBP, as the designated real-time control point always occurred when complete nitrification was achieved. Under real-time control, the bio-chemical reaction in the system was artificially maintained until the system reached a target oxidation status. For this reason, optimal conditions for microbes can be maintained by switching the reaction phases when no external nutrient exists in the solution [21].

The NO<sub>x</sub>-N concentration in the final effluent gradually increased as the NH<sub>4</sub>-N loading rate increased. This is due to insufficient organic matter in the influent; the average C/N ratio (TOCs/soluble inorganic N) of the influent was 1.1 in this study. By using the real-time control strategy, complete nitrification of NH<sub>4</sub>-N always occurred, but incomplete denitrification was observed during the 12-h anoxic phase because of the low C/N levels in the influent. The average NO<sub>x</sub>-N concentrations in Runs I and II were 23



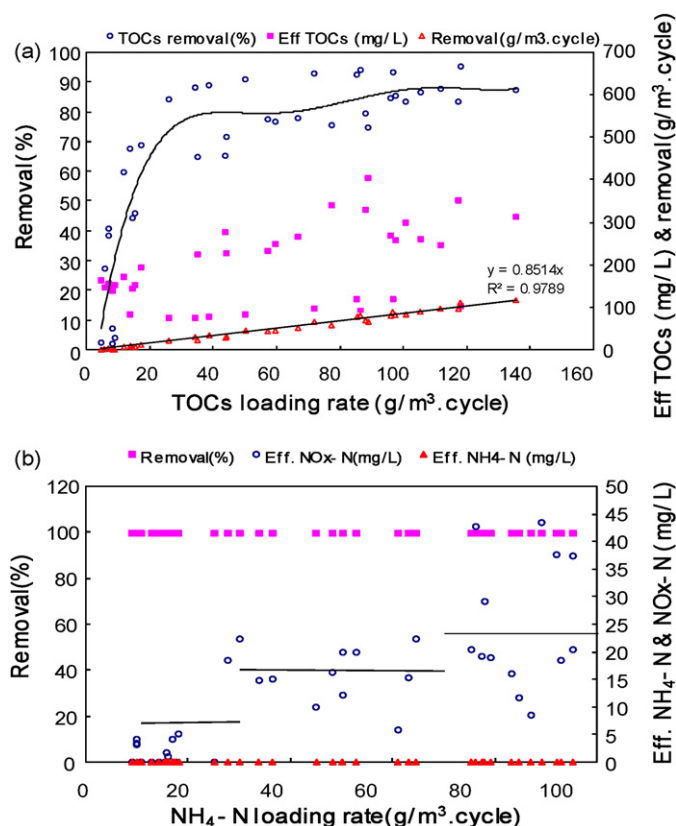


Fig. 6. Removal characteristics of organic matter and nitrogen.

and 8 mg/L, respectively. Indeed, the concentration in Run I is 2.9 times higher than that in Run II (Table 2), and this was positively correlated to the NH<sub>4</sub>-N levels in the influent. Since the NH<sub>4</sub>-N level in the influent was 2.9 times higher in Run I, the loading rate per cycle should likewise be higher in Run I. Consequently, the above assertion results in proportionally higher NO<sub>x</sub>-N levels in Run I. However, if sufficient organics existed or an external carbon source was supplemented during operations, the relationship between the NO<sub>x</sub>-N level in the final effluent and the NH<sub>4</sub>-N loading rate would not be observed. A low C/N ratio in the influent can be a limiting factor with regard to the removal of nitrogen from wastewater because incomplete denitrification occurs in the reactor [19]. In the case of a low C/N ratio, a suitable carbon source should be added for complete denitrification and to maintain ideal BNR (Biological Nutrient Removal) conditions [3]. C/N is an important indicator of the efficiency of nitrogen removal and proper biological phosphorus removal from wastewater.

#### 4. Conclusion

In this experiment, real-time control of the swine wastewater treatment process using the pH (mV)-time profile was studied. Based on the results of this study, the pertinent information can be summarized as follows:

1. Upon the completion of nitrification in the oxic phase, the MSC ( $r = 5$ ) of the pH (mV) moved into the negative range, and we were consistently made aware of this NBP by monitoring the MSC-pH (mV). However, such an NBP was not found on the ORP-time profile in many cases.
2. Even when no NBP was observed on the ORP profile, real-time control of the oxic phase using the MSC-pH (mV) was very successful. We removed 100% of NH<sub>4</sub>-N and produced a similar

effluent quality despite great differences in influent concentrations and loading rates.

3. NKPs were observed on both the ORP and pH (mV) profiles at the time of complete denitrification in the anoxic phase. However, the NKP on the pH (mV)-time was not obvious in many cases, indicating that the ORP may be a more reliable real-time control parameter for the anoxic phase than the pH (mV).
4. A very high positive correlation ( $r^2 = 0.98$ ) was found between the loading rate and TOCs removal, and a loading rate of 100 g/m<sup>3</sup>/cycle was determined to be optimum for TOCs removal.

#### Acknowledgements

This research was funded by ARPC (agricultural R&D Promotion Center), Korea. Also, this work was supported in part by a grant from the institute of Animal Resources at Kangwon National University, Korea.

#### References

- [1] C.S. Ra, K.V. Lo, D.S. Mavinic, Real-time control of two stage sequencing batch reactor system for the treatment of animal wastewater, *Environ. Technol.* 19 (1998) 343–356.
- [2] L.W. Deng, P. Zheng, Z.A. Chen, Anaerobic digestion and post-treatment of swine wastewater using IC-SBR process with bypass of raw wastewater, *Process. Biochem.* 41 (2006) 965–969.
- [3] J.H. Kim, M. Chen, N. Kishida, R. Sudo, Integrated real-time control strategy for nitrogen removal in swine wastewater treatment using sequencing batch reactors, *Water Res.* 38 (2004) 3340–3348.
- [4] J. Dosta, J. Rovira, A. Gali, S. Mace, J.M. Alvarez, Integration of a coagulation/flocculation step in a biological sequencing batch reactor for COD and nitrogen removal of supernatant of anaerobically digested piggery wastewater, *Bioresour. Technol.* 99 (2007) 5722–5730.
- [5] N. Bernet, N. Delgenes, J.C. Akunna, J.P. Delgenes, R. Moletta, Combined anaerobic-aerobic SBR for the treatment of piggery wastewater, *Water Res.* 34 (2000) 611–619.
- [6] D.I. Masse, R.L. Droste, Comprehensive model of anaerobic digestion of swine manure slurry in a sequencing batch reactor, *Water Res.* 34 (2000) 3087–3106.
- [7] W.N. Jern, A sequencing batch anaerobic reactor for treating piggery wastewater, *Biol. Wastes* 28 (1989) 39–51.
- [8] N. Bernet, N. Delgenes, R. Moletta, Denitrification by anaerobic sludge in piggery wastewater, *Environ. Technol.* 17 (1996) 293–300.
- [9] S. Wang, J. Ma, B. Liu, Y. Jiang, H. Zhang, Degradation characteristics of secondary effluent of domestic wastewater by combined process of ozonation and biofiltration, *J. Hazard. Mater.* 150 (2008) 109–114.
- [10] C.S. Ra, K.V. Lo, D.S. Mavinic, Control of a swine manure treatment process using a specific feature of oxidation reduction potential, *Bioresour. Technol.* 70 (1999) 117–127.
- [11] B.S. Akin, A. Ugurlu, Monitoring and control of biological nutrient removal in a Sequencing Batch Reactor, *Process. Biochem.* 40 (2005) 2873–2878.
- [12] S. Puig, L. Corominas, M.T. Vives, M.D. Balaguer, J. Colprim, Development and implementation of a real-time control system for nitrogen removal using OUR and ORP as end points, *Ind. Eng. Chem. Res.* 44 (2005) 3367–3373.
- [13] A. Spagni, J. Buday, P. Ratini, G. Bortone, Experimental consideration on monitoring ORP, pH, conductivity and dissolved oxygen in nitrogen and phosphorus biological removal process, *Water Sci. Technol.* 43 (2001) 197–204.
- [14] B.K. Li, P.L. Bishop, Oxidation–reduction potential changes in aeration tanks and microprofiles of activated sludge floc in medium- and low-strength wastewaters, *Water Environ. Res.* 76 (2004) 394–403.
- [15] W. Shuying, Z. Shanfeng, P. Chengyao, A. Takigawa, Intercross real-time control strategy in alternating activated sludge process for short-cut biological nitrogen removal treating domestic wastewater, *J. Environ. Sci.* 20 (2008) 957–963.
- [16] Z. Han, W. Wu, J. Zhu, Y. Chen, Oxidation–reduction potential and pH for optimization of nitrogen removal in a twice-fed sequencing batch reactor treating pig slurry, *Biosyst. Eng.* 99 (2008) 273–281.
- [17] D. Gao, Y. Peng, B. Li, H. Liang, Shortcut nitrification–denitrification by real-time control strategies, *Bioresour. Technol.* 100 (2009) 2298–2300.
- [18] D. Obaja, S. Mace, J. Costa, C. Sans, J.M. Alvarez, Nitrification, denitrification and biological phosphorus removal in piggery wastewater using a sequencing batch reactor, *Bioresour. Technol.* 87 (2003) 103–111.
- [19] N. Kishida, J.H. Kim, M. Chen, H. Sasaki, R. Sudo, Effectiveness of oxidation–reduction potential and pH as monitoring and control parameters for nitrogen removal in swine wastewater treatment by sequencing batch reactors, *J. Biosci. Bioeng.* 96 (2003) 285–290.
- [20] American Public Health Association (APHA), Standard Methods for the Examination of Water and Wastewater, 19th ed., Washington, DC, 1995.
- [21] C.S. Ra, K.V. Lo, J.S. Shin, J.S. Oh, B.J. Hong, Biological nutrient removal with an internal organic carbon source in piggery wastewater treatment, *Water Res.* 34 (2000) 965–973.

- [22] J.B. Holman, D.G. Wareham, COD, ammonia and dissolved oxygen time profiles in the simultaneous nitrification/denitrification process, *Biochem. Eng.* 22 (2005) 125–133.
- [23] H. Guo, J. Zhou, J. Su, Z. Zhang, Integration of nitrification and denitrification in airlift bioreactor, *Biochem. Eng.* 23 (2005) 57–62.
- [24] S.M. Libelli, Control of SBR switching by fuzzy pattern recognition, *Water Res.* 40 (2006) 1095–1107.
- [25] H. Kim, O.J. Hao, pH and oxidation–reduction potential control strategy for optimization of nitrogen removal in an alternating aerobic–anoxic system, *Water Environ. Res.* 73 (2001) 95–102.
- [26] L. Deng, P. Zheng, Z. Chen, Q. Mahmood, Improvement in post-treatment of digested swine wastewater, *Bioresour. Technol.* 99 (2008) 3136–3145.