pH and Oxidation–Reduction Potential Control Strategy for Optimization of Nitrogen Removal in an Alternating Aerobic–Anoxic System

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ABSTRACT: An alternating aerobic and anoxic (AAA) system is a continuous-flow, activated-sludge process in which the environmental conditions necessary to meet the specific requirements for aerobic nitrification and anoxic denitrification are created. Because of stricter regulations on wastewater effluent and concerns on energy consumption, the process control of the system is now becoming more important. A bench-scale AAA system with different fixed aeration ratios was operated for more than 8 months to evaluate effects of the total cycle time and aeration ratio on the system performance and to develop a feasible control scheme. With supplemental organic addition, the system shows removal efficiencies of 85 to 90% and 78 to 82% for chemical oxygen demand and total nitrogen, respectively. The oxidation–reduction potential (ORP) and pH profiles indicate that the aerobic cycle can be controlled by a control point (ammonia valley) on the pH profile indicating the end of nitrification and the anoxic cycle controlled by another point (nitrate knee) on the ORP profile signifying the end of denitrification. Thus, a dual control strategy with the pH and ORP control points was used for terminating aerobic–anoxic and initiating anoxic–aerobic cycles in an AAA system. The performance of the online control system is excellent, with a significant energy saving (average aeration ratio, $f_a = 0.23$) as compared to the fixed time systems ($f_a = 0.33$ to approximately 0.5). *Water Environ. Res.,* **73,** 95 (2001).

KEYWORDS: activated sludge, alternating aerobic–anoxic, process control, nitrogen removal, pH, oxidation–reduction potential.

Introduction

An alternating aerobic and anoxic (AAA) system is a continuous-flow, activated-sludge process in which the environmental conditions necessary to meet the specific requirements for aerobic nitrification and anoxic denitrification are created. During the air-on period, ammonium (NH_4^+) is converted to nitrate (NO_3^-) by autotrophs and NO_3^- is then reduced to nitrogen gas by heterotrophs during the air-off period. In these cyclic reactions, the alkalinity previously consumed during the aerobic state is partially recovered during the subsequent anoxic period, maintaining a relatively stable system. With proper control and operation, this system can reduce domestic wastewater total nitrogen (TN) concentrations to average values less than 8 mg/L (Bachelor, 1983). However, because of the scarcity of full-scale plant operation data and the difficulty in controlling the duration of each cycle, there are only a few full-scale applications of this process (Morgan et al., 1999, and Nakajima and Kaneko, 1991).

Stricter regulations on wastewater effluent, space limitations on the treatment site, and energy consumption issues have heightened the importance of modifying biological wastewater treatment processes using process control. Because the aeration cycle time and influent composition affect AAA system performance, the AAA operation with a predetermined fixed aeration cycle ratio often fails to operate optimally. The ability to initiate the aeration and control the duration of air-on periods has been a primary consideration in the design and operation of AAA systems, not only for achieving nitrogen removal, but also for minimizing energy consumption. The aeration may account for 80% of total electrical consumption of a plant (Charpentier and Martin, 1996). With proper operation, a significant cost saving may be associated with the aeration energy. The air-off periods should be long enough for complete denitrification, but not so long that there are odor problems or a secondary phosphate release in a nitrogen removal system. Consequently, real-time control strategies to remove TN and to save energy are essential in the AAA system.

Total cycle time, t_c (e.g., 2 hours in a 1-hour air-on and 1-hour air-off system), and aeration ratio, f_a (e.g., 0.5 in the above case), are important parameters in AAA systems (Bachelor, 1982 and 1983). There are several control strategies to adjust t_c and f_a. The most straightforward approach is to rely on an online ammonia analyzer to indicate the end of nitrification; hence, the aeration can then be terminated and the anoxic period initiated. The NO_3^- analyzer would be used to determine the end of denitrification and to initiate the aeration. Although such instruments have been used for process control of different alternating systems (Isaacs and Temmink, 1996; Thomsen and Kisbye, 1996; and Thornberg et al., 1993), these analyzers require extensive sample pretreatment and, hence, considerable maintenance. The lack of their use in the United States renders this approach impractical. However, the approach based on an online analyzer may be widely applied in the near future as a result of the noticeable advances in sensor technology made in recent years (LeBlanc and Sorkin, 1999).

The second approach is to use a model-based control strategy (Coen et al., 1997, and McAvoy et al., 1999) so that model-predicted ammonia and NO_3^- results will be used to terminate and initiate aerobic and anoxic periods. Unfortunately, a good model such as Activated Sludge Model No. 1, has many dimensions and possesses a large number of kinetic and stoichiometric parameters. As a result, it presents a significant computational hindrance for performing simulations and analysis.

The third approach is to interpret the signal from online NADH sensors that monitor biomass activity. This approach has been successfully applied to a full-scale plant (Armiger et al., 1993).

However, it requires an expert to interpret signals and determine the start or end of each phase, which is not suitable for a small plant.

The fourth approach for online control is to use several control points in the oxidation–reduction potential (ORP) and pH profiles. Because of their low cost and small maintenance requirements, ORP and pH have been demonstrated to be practical and useful for process control for activated-sludge processes (Charpentier et al., 1998, and Sasaki et al., 1993), digestion (Al-Ghusain and Hao, 1995), other oxidation–reduction processes (Chang et al., 1996), and disinfection (Kim and Hensley, 1997). Specifically, several investigators have identified the *nitrate knee* in the ORP profile, which indicates the end of denitrification (Koch and Oldham, 1985), and *ammonia valley* in the pH profile, which signifies the end of nitrification (Al-Ghusain et al., 1994). Unfortunately, none of these studies actually used the combination of these two probes (pH and ORP) for process control in AAA systems.

In the present study, an AAA system is operated with various f_a ratios and t_c at a constant mean cell residence time (MCRT) and hydraulic residence time (HRT). The primary objective is to verify whether these control points are consistently present under different operating conditions. The second objective is then to provide a rational control scheme based on these control points. Finally, the third goal is to apply the control scheme to an AAA system and evaluate its performance, specifically with respect to nitrogen removal efficiency and energy savings under various loading conditions.

Materials and Methods

Sludge and Wastewater. The seed sludge for the bench-scale reactor was obtained from the Parkway Wastewater Treatment Plant, Bowie, Maryland. The primary effluent, collected twice weekly and stored in a refrigerator, was used as the feed to the reactor.

Reactor System. A bench-scale reactor (4 L) was used with a continuous alternation between air-on and air-off. Saturated air was used for aeration and mixing in the reactor during air-on periods. Additional mixing to the reactor during air-off periods was provided by a magnetic stirrer. The system was equipped with solid-state relays and a solenoid valve for turning air on or off. The system was continuously monitored with ORP (Mettler Toledo Type Pt4805-DPAS-SC, Woburn, Massachusetts) and pH probes (Mettler Toledo Type 405-SC-DPAS). The probes were cleaned and calibrated once or twice a week and showed good performance during the entire study period. A data acquisition and control system was used for pH and ORP input (from the sensors and meters) and output (to digital signals) and for setting the air on–off.

The influent feed (immersed in an ice-water tank) was transferred to the reactor by a peristaltic pump (Cole-Palmer Masterflex 7518-00, Vernon Hills, Illinois) at a constant HRT (12 hours). A MCRT of 12 days was maintained by wasting an appropriate amount of mixed liquor directly from the reactor at the end of the aerobic phase. Aeration cycle times/total cycle times of 1.5 hours/3.0 hours, 1 hour/3.0 hours, 1 hour/2.5 hours, and 1 hour/2 hours were used for phases I, II, III, and IV, respectively. In phase V, the system was operated based on the control points on the pH and ORP profiles.

Samples for dynamic studies were collected directly from the reactor. The influent samples were collected from the influent reservoir just after it was refilled. Effluent samples were taken from the effluent storage tank. Conventional parameters such as mixed liquor volatile suspended solids (MLVSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), NH_4^+, NO_3^-, pH, and alkalinity were routinely analyzed. All of the parameters in the study were analyzed according to *Standard Methods* (APHA et al., 1995).

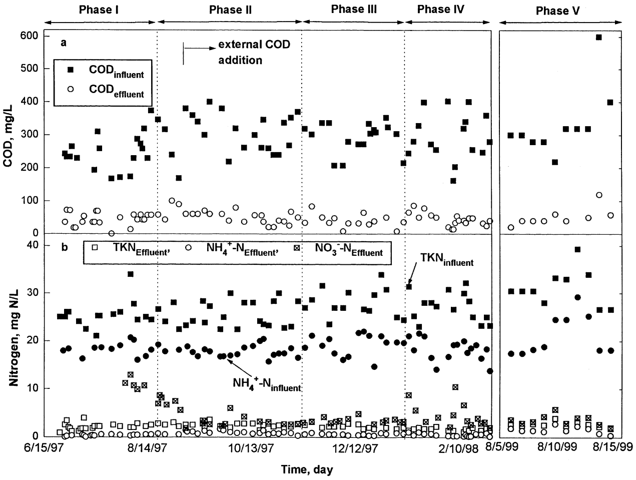

Figure 1—Overall performance of the AAA system.

Results and Discussion

Overall Performance (Fixed t_c and f_a). Data on daily average COD, NO_3^-, and NH_4^+ concentrations of the influent and effluent for the entire study period with the fixed cycle ratios are presented in Figure 1. Influent concentrations fluctuated between 150 and 450 mg/L COD, 20 and 35 mg/L TKN, and 15 and 25 mg/L NH_4^+. Overall, the system maintained low effluent NH_4^+ concentrations (less than 1 mg N/L, Table 1). Data shown in Figure 1, however, indicate that the NO_3^- generated through nitrification was not completely removed from the system in Phase I (56% TN removal, Table 1). Thus, the f_a was lowered to 0.33 with further supplementary organic addition (sodium acetate equivalent to COD 80 to 120 mg/L) during the phase II study; the system then showed adequate denitrification (Figure 1). The high NO_3^- concentrations were also detected when acetate was not added to the feed during several periods in phase IV (Figure 1). Overall, the system could maintain an effluent TN less than or equal to 6 mg/L.

The effect of f_a on NH_4^+ removal is negligible, although it seems that effluent NO_3^- is proportional to the system's f_a (Table 1). When the f_a was increased from 0.33 (phase II) to 0.5 (phase IV), the effluent NO_3^- concentration increased from 2.9 to 4.5 mg N/L. Therefore, it is critical to provide sufficient anoxic cycle time to remove NO_3^- from the system; the system, however, may experience undesirable, prolonged anaerobic conditions at low f_a values.

Figure 2 presents one example of the dynamics of NH_4^+, NO_3^-, and alkalinity variations from phase II studies (1 hour air-on and 2 hours air-off). The well-established features are easily identified, including nitrification (air-on periods), denitrification (air-off periods), ammonification (air-off), alkalinity reduction and generation, and zero-order nitrification–denitrification rates. Note that a slight increase in NO_3^- concentrations after the disappearance of NH_4^+ during the air-on periods is caused by further oxidation of the newly formed NH_4^+ via ammonification. The specific nitrification and denitrification rates throughout the dynamic studies ranged

Table 1—Overall performance of an AAA system.[a]

	Phase I, t_c = 3 hours and f_a = 0.5 (air on/off 1.5 hours/1.5 hours)			Phase II, t_c = 3 hours and f_a = 0.33 (air on/off 1 hours/2 hours)			Phase III, t_c = 2.5 hours and f_a = 0.4 (air on/off 1 hours/1.5 hours)			Phase IV, t_c = 2 hours and f_a = 0.5 (air on/off 1 hours/1 hours)			Phase V, t_c = 2.85 hours and f_a = 0.23 (air on/off 0.65 hours/2.2 hours)		
Parameters	**Influent, mg/L**	**Effluent, mg/L**	**Removal, %**	**Influent, mg/L**	**Effluent, mg/L**	**Removal, %**	**Influent, mg/L**	**Effluent, mg/L**	**Removal, %**	**Influent, mg/L**	**Effluent, mg/L**	**Removal, %**	**Influent, mg/L**	**Effluent, mg/L**	**Removal, %**
Wastwater															
Total COD	270 (57)[b]	45 (20)	83	310 (59)	47 (21)	85	320 (46)	32 (21}	90	400 (77)	48 (17)	88	330 (104)	52 (28)	84
TN	28.8 (2.6)	12.6 (2.6)	56	29.3 (2.7)	5.4 (2.1)	82	30.1 (3.3)	5.5 (2.0)	82	27.2 (2.9)	6.0 (2.7)	78	31.4 (3.9)	6.4 (1.7)	80
Organic nitrogen	10.4 (1.8)	1.8 (0.4)	83	11.3 (1.5)	1.7 (0.7)	85	10.8 (3.0)	1.3 (0.4)	88	9.6 (2.1)	1.1 (0.3)	89	10.3 (4.5)	1.2 (0.5)	88
NH_4^+ nitrogen	18.4 (1.4)	0.4 (0.2)	98	18 (1.3)	0.8 (0.3)	96	19.3 (2.2)	0.6 (0.2)	97	17.6 (2.2)	0.4 (0.2)	98	21.1 (4.3)	1.6 (0.7)	92
NO_3^- nitrogen	—	10.4 (1.9)	—	—	2.9 (1.6)	—	—	3.6 (1.6)	—	—	4.5 (2.4)	—	—	3.6 (1.1)	—
Alkalinity	141 (10)	56 (7.4)	—	160 (8.6)	114 (10)	—	175 (30)	120 (24)	—	160 (14)	95 (19)	—	198 (26)	148 (21)	—
Sludge															
MLVSS, mg/L		1630 (242)			1490 226)			1800 (212)			1960 (158)			2040 (164)	
Specific rates, mg N/g MLVSS·h[c]															
Nilnification		1.9			4.2 (3.6–5.3)			4.9 (4.8–5.3)			2.1			4.9	
Denitrification		3.4			3.7 (2.5–4.6)			3.2(2.3–3.9)			2.9			2.9	

[a] MCRT = 12 days, HRT = 12 hours, and reactor temperature = 25 ± 2°C.
[b] Effluent data were used only after supplemental COD addition.
[c] t_c and f_a are average values for 10 days real-time operation.
[d] Values in ( ) represent standard deviation.
[e] Data based on the average of five sets of data in phase II and three sets in phase III.

from 1.9 to 4.9 mg NH_4^+/g MLVS·h and 2.9 to 3.7 mg NO_3^-/g MLVSS·h, respectively, for the four phases (Table 1). These values are comparable with those reported by others, such as a specific nitrification rate of 1.8 to 4.3 mg NH_4^+/g MLVSS·h and a denitrification rate of 2.2 to 5.2 mg NO_3^-/g MLVSS·h (Aoi et al., 1992; Hao and Huang, 1996; and Yu et al., 1998). The average stoichiometric ratio between alkalinity and NH_4^+ consumption was calculated to be 8.5 mg calcium carbonate ($CaCO_3$)/mg NH_4^+, which is slightly greater than the theoretical value of 7.1 mg $CaCO_3/NH_4^+$. The average ratio between alkalinity recovery and NO_3^- consumption was 3.8 mg $CaCO_3$/mg NO_3^-, close to the theoretical value, 3.6 mg $CaCO_3$/mg NO_3^-.

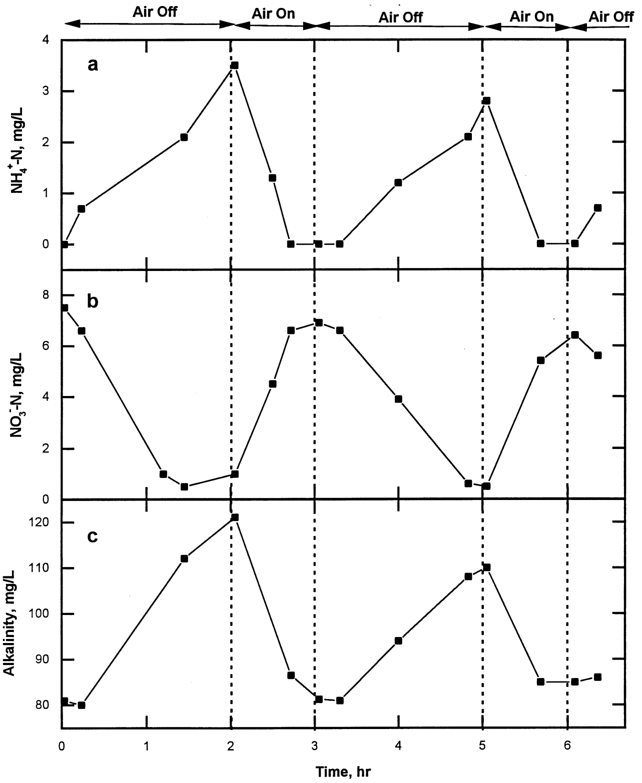

Figure 2—Dynamics of NH_4^+, NO_3^-, and alkalinity of two cyclic modes.

Two cycles of the ORP and pH profiles along with the NO_3^- and NH_4^+ dynamic profiles are presented in Figure 3. Both ORP (Figure 3b) and pH (Figure 3c) were found to vary with the aerobic–anoxic cycles as a result of sequential nitrification and denitrification in the AAA reactor. The ORP remained relatively constant during the transient period after the air had been turned off because of residual dissolved oxygen (DO) (not shown); thereafter, the ORP dropped significantly because of anoxic denitrification. The transient period varied with the influent composition; the greater the influent biodegradable COD concentration, the shorter the period. Also, the pH drops caused by nitrification and increases caused by denitrification are clearly identified (Figure 3c).

Two significant points on the pH and ORP profiles are easily discerned as suggested in the literature. The nitrate knee on the ORP curve (Figure 3b) is described as the point where NO_3^- in the system is significantly removed; only a small amount of NO_3^- (less than 0.5 mg) is detected. Thereafter, the system shifts into a true anaerobic condition resulting in a further rapid decrease in ORP. The ammonia valley on the pH curve (Figure 3c) corresponds to the end of nitrification. There clearly exists a local minimum in the pH profiles; pH increases after the ammonia valley.

Several other features identified in Figure 3 are not consistently present. These include the *nitrate apex* (Al-Ghusain and Hao, 1995) in the pH profile, corresponding to the nitrate knee of the ORP profile, and the *DO elbow* (Wareham et al., 1994) in the ORP profiles, corresponding to the ammonia valley of the pH profiles. Consequently, the significant points of the nitrate apex and DO elbow cannot be effectively used as real-time control points.

Control Strategies. For nitrogen removal in the AAA process, the conventional controls with DO and oxygen uptake rate cannot be used because they cannot distinguish between an anoxic and anaerobic state. Practically, ORP and pH profiles can be used because of the consistent presence of significant points, instrumental reliability, and their requirement of minimum maintenance. The results of this study indicate that both ORP and pH could be applied to control a particular AAA system, specifically, the ammonia valley on the pH profiles for nitrification and the nitrate knee on the ORP profiles for denitrification. The absolute values of the pH data corresponding to the ammonia valley and ORP values of the nitrate knee cannot be used as the control points because of their variability. Rather, the derivatives of these values should be used. Figure 4 shows the derivatives of the ORP profiles, indicating that there are two valleys in the dORP/d*t* profile (Figure 4b) during air-off periods. The first one is caused by the shift from oxygen to NO_3^- respiration, and the second one is the result of the change from anoxic to anaerobic conditions. The latter change involves the nitrate knee, or the end of denitrification, where $d^2ORP/dt^2 = 0$ (Figure 4c). In the ammonia valley, dpH/d*t* changes from a negative to positive value (Figure 5b). This inflection point ($dpH/dt = 0$) can then be used to determine the end of nitrification.

The dual control strategy presented in Figure 6 requires the calculation of a moving average of pH–ORP data for noise control. Approximately 1200 pH–ORP data points were collected in 1 minute and averaged every 2 minutes. During air-on cycles, the dpH/d*t* profile is monitored to detect the ammonia valley where $dpH/dt = 0$. To skip the first point of $dpH/dt = 0$, which is not the ammonia valley (the beginning of the nitrification and dpH/d*t* changes from a positive to a negative value), a narrow dpH/d*t* band

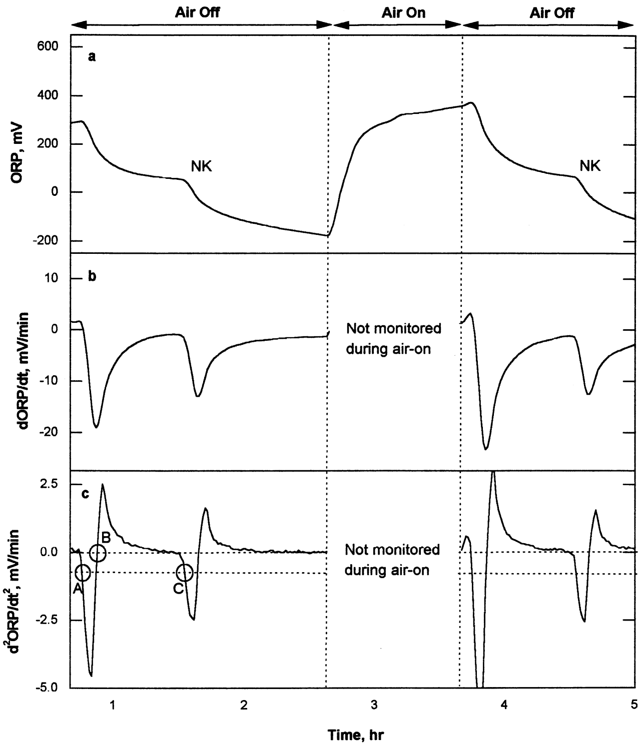

Figure 4—Moving averages of ORP, dORP/d*t* and d^2ORP/dt^2 profiles. NK: nitrate knee.

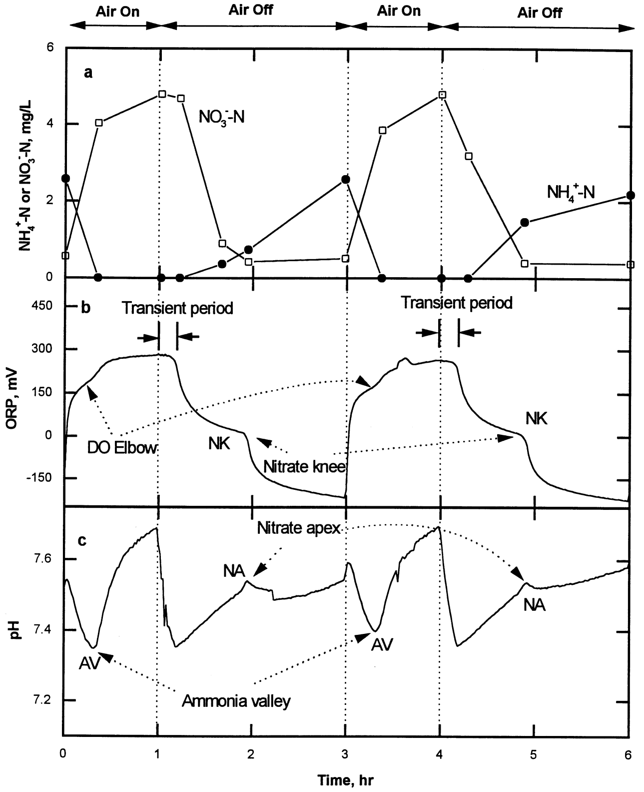

Figure 3—NH_4^+ and NO_3^- dynamics along with ORP and pH profiles.

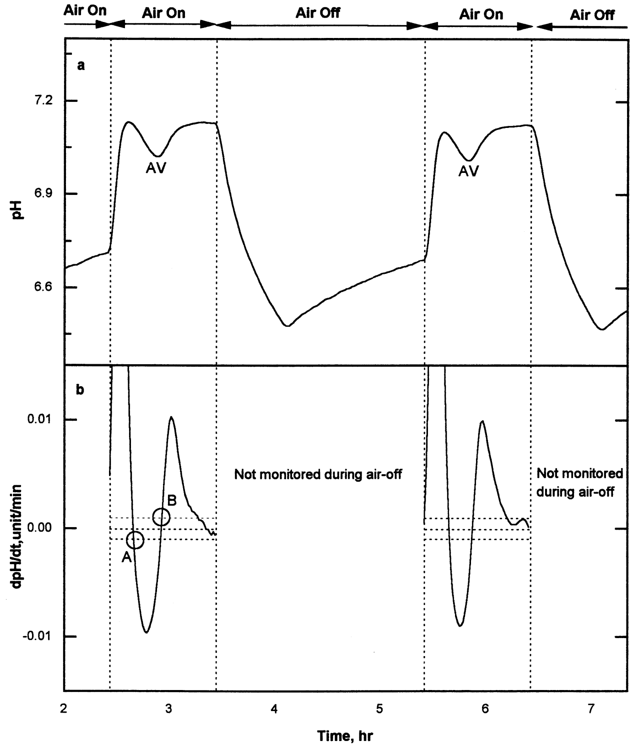

Figure 5—Moving averages of pH and dpH/d*t* profiles. AV: ammonia valley.

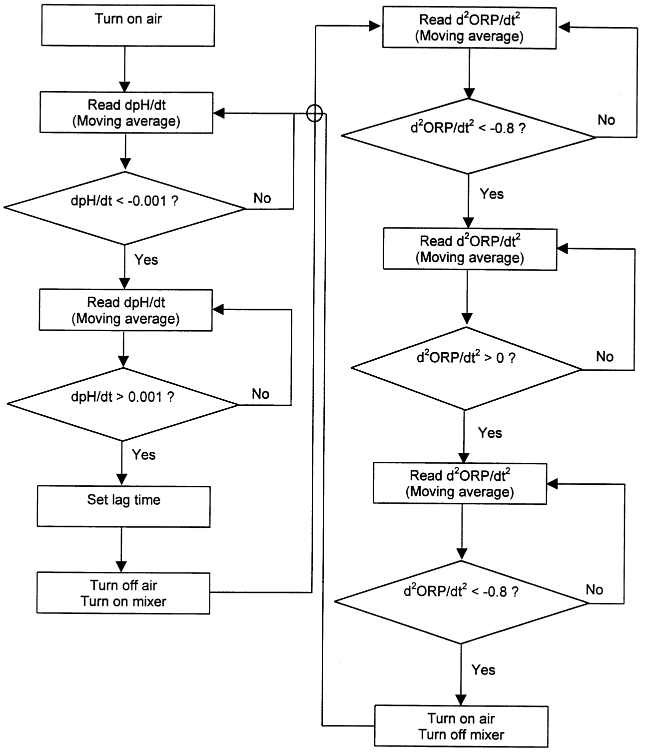

Figure 6—Control strategy with d^2ORP/dt^2 and dpH/dt.

(from −0.001 to 0.001, Figure 5b) is used for detecting the second point of $dpH/dt = 0$. Once the air is turned on, the system first detects a negative point in the dpH/dt profile; less than or equal to -0.001 (A in Figure 5b) and then a positive point greater than or equal to 0.001 (B in Figure 5b). Thus, the point at the end of nitrification can be easily detected. The aeration was actually terminated 10 minutes after the detection of the ammonia valley to ensure complete ammonia removal. A similar approach can be used for detecting the nitrate knee. Again, an arbitrary value of d^2ORP/dt^2 of −0.8 (Figure 4c) is used to skip the first two points of $d^2ORP/dt^2 = 0$, which are not the nitrate knee. After air is turned off, the system first detects a point less than or equal to −0.8 in the d^2ORP/dt^2 profile (A in Figure 4c), then another point greater than or equal to 0 (B in Figure 4c), and finally the point less than or equal to −0.8 (C in Figure 4c); the last point is the nitrate knee.

Overall Performance (with Online Control). The control scheme presented above was applied to a new bench-scale AAA system in phase V. The sludge–wastewater for the study with real-time control strategy was also taken from the same wastewater plant as was before. The overall performance of the system with the control scheme shown in Table 1 and Figure 1 is comparable with that obtained from a fixed f_a value. The COD and TN removal efficiencies are 84 and 80%, respectively. The average effluent NH_4^+ concentration of 1.6 mg/L is slightly greater than that obtained before, a result of the build-up of NH_4^+ in the reactor during prolonged anoxic cycle durations. The average effluent NO_3^- level was 3.6 mg/L. The average f_a during 10 days operation was approximately 0.23 (0.65 hours of air-on and 2.2 hours of air-off). Therefore, compared to the previous system with fixed f_a values (0.33 to 0.5), a significant amount of aeration energy is reduced (30 to 54%) in the system with online control and the effluent TN is maintained at the same level.

Figure 7 shows 6 cycles of the pH and ORP profiles in the AAA system operated by the control point uses of the ammonia valley and nitrate knee. The system turns air on or off properly according to the strategy in Figure 6; the aeration is terminated within 10 minutes of detecting the ammonia valley. Figure 8 shows the dynamic studies of NH_4^+, NO_3^-, and alkalinity. Again, the features described before are well defined. The specific nitrification and denitrification rates are 4.9 and 2.9 mg N/g MLVSS·h, respectively.

To ensure that the control strategy is able to handle variable conditions, the system was subject to nitrogen, COD, and flow-shock loadings. The results of raising influent ammonia (TKN was approximately 50 mg/L) for 8 hours are shown in Figure 9. Both air-on and air-off cycle times were extended to remove all of the NH_4^+ from the influent and NO_3^- generated from nitrification. The prolonged anoxic duration causes the buildup of NH_4^+ in the system and results in the increase of effluent nitrogen. Although the composite effluent collected after 8 hours shock loading shows rather high NH_4^+ (4.2 mg N/L) and NO_3^- (6.5 mg N/L) concentrations, the system was able to recover once the additional ammonia loading was removed. Ammonia and NO_3^- concentrations reduced to 1.8 and 3.8 mg N/L, respectively. Overall, the results are better than those of a similar shock loading study with the system based on a fixed cycle time of 1 hour air-on and 2 hours air-off with a NO_3^- concentration of 8.6 mg N/L (not shown). The denitrification is simply incomplete within the specified 2-hour anoxic time.

The results of the pH and ORP profiles in the system with a hydraulic shock loading condition (two times the flowrate) are

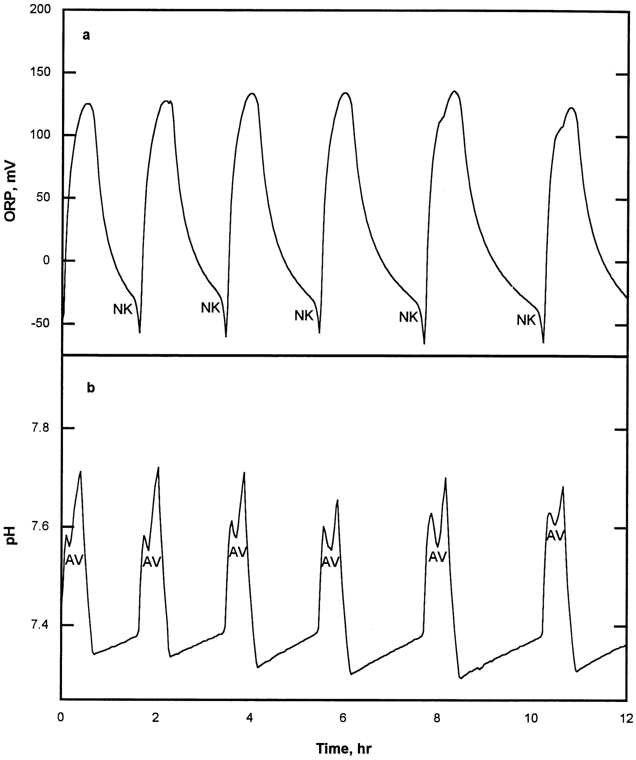

Figure 7—Six cycles of ORP and pH profiles of the online control AAA system.

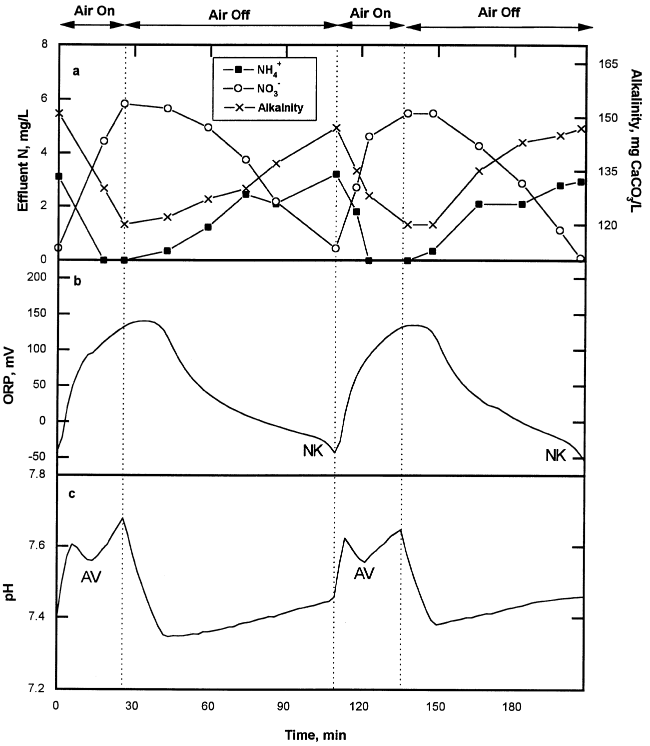

Figure 8—NH_4^+, NO_3^-, alkalinity and ORP/pH profiles of the online control AAA system.

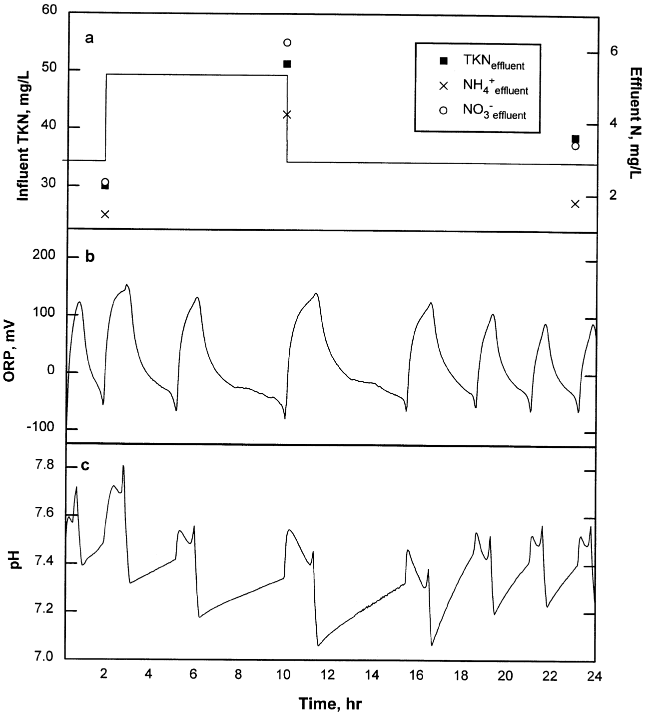

Figure 9—Effluent quality and ORP/pH profiles of the online control AAA system under nitrogen shock loading conditions (solid line of the top figure represents influent TKN concentration).

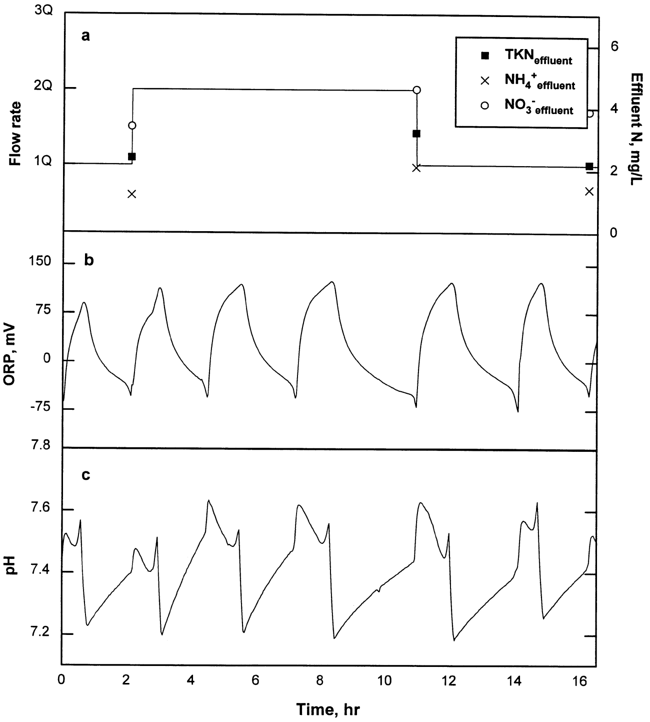

Figure 10—Effluent quality and ORP/pH profiles of the online control AAA system under flow shock loading conditions (solid line of the top figure represents influent flow rate).

shown in Figure 10. Again, all of the control points involving the nitrate knee and ammonia valley were detected and the control strategy was followed to allow prolonged denitrification and nitrification durations. The concentrations of the effluent nitrogen species collected before and after the shock loading do not vary too much (Figure 10a). The daily average of NH_4^+ and NO_3^- were 1.7 and 4.2 mg N/L, respectively. The daily average aeration ratio on the day when the hydraulic loading study was performed was approximately 0.32.

Constraints with Online Control. Although the online control with pH and ORP profiles can be easily implemented, there are two concerns associated with the anoxic cycle control for extremely high or low COD loadings. When the influent COD:TKN is high (e.g., 600 mg COD:27 mg N, in the case of Figure 11), ORP readings fall rapidly without the nitrate knee being detected (Figure 11a). Yet the nitrate apex on the pH profile (Figure 11b) clearly indicates the end of denitrification approximately 20 minutes after the anoxic cycle. Therefore, a constraint value for the ORP profile should be selected to initiate aeration. From all of the ORP profiles obtained from the present study, an ORP constraint value of −120 mV could be used. The ORP profiles of the AAA system with such a constraint are shown in Figure 11c, which indicates that the first three anoxic cycles were terminated by the ORP constraint. Afterward, the denitrification duration is determined by the detection of the nitrate knee. For this particular run, the effluent NH_4^+ and NO_3^- concentrations are low (0.4 and 2.0 mg N/L, respectively).

For the case of low influent COD:TKN ratios, the anoxic period may be too long to ensure complete denitrification because the rate for NO_3^- endogenous respiration is too slow. The consideration of complete NO_3^- removal may not be warranted because of the

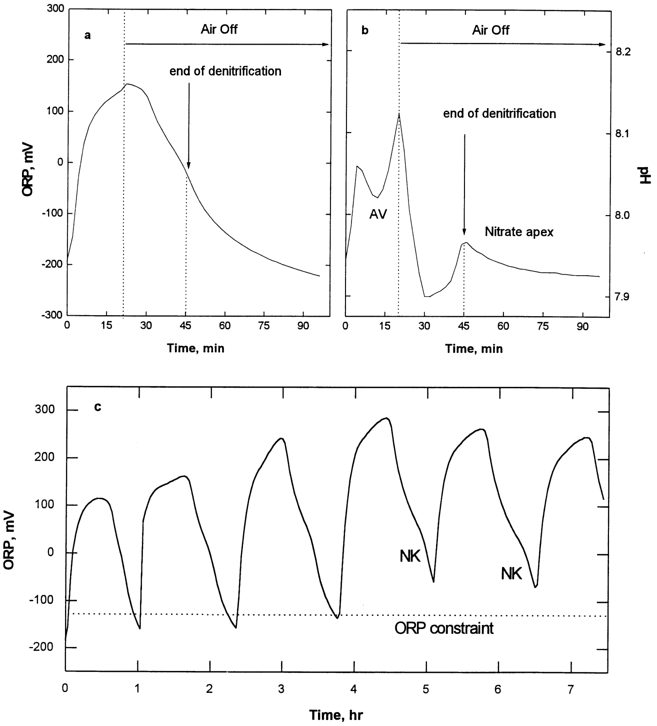

Figure 11—The ORP and pH profiles of the AAA system with high COD/TKN ratios.

buildup of NH_4^+ in the system. In one experiment in which acetate was not added to the feed, the system showed a long denitrification time (6 hours), resulting in the accumulation of NH_4^+ (2.8 mg N/L) (not shown). Thus, it is reasonable to set a constraint (e.g., a maximum of 3 hours) for the denitrification period.

Questions about a suitable location of probes because of inhomogeniety of a reactor and about possible failures of the probes need to be addressed. Although Vanrollneghem and Coen (1995) have suggested the placement of the probes at the end of a plug-flow reactor for detecting nitrate knee, it is not possible for the proposed system to be used in such plug-flow systems. The probe signals will not reflect the trends shown in a completely mixed system (e.g., Figure 3); the proposed system is only applicable to a completely mixed scheme.

For a completely mixing system, several probes each for pH and ORP monitoring should be installed. A program can be written to monitor signals from all of the probes but screen out signals from any malfunctioning probes. Before the initiation of the anoxic phase, the detection of the ammonia valley should be observed by all of the probes. This will ensure a conservative approach for plant operation (i.e., probe 1 detects the ammonia valley at 1.1 hours, while probe 2 detects it at 1.3 hours; the latter would be the control factor). Regarding possible air diffuser fouling, membrane diffusers are favored over ceramic diffusers (Solley and Barr, 1999). Also, during the anoxic period, the intensity of aeration may be reduced to create an anoxic state to prevent problems associated with frequently turning a compressor on and off.

Conclusions

A bench-scale AAA system was operated for more than 8 months to evaluate the effects of the total cycle time and aeration ratio on the system performance and develop a feasible control scheme. The AAA system with fixed f_a values shows excellent removal efficiencies of COD (85 to 90%) and TN (78 to 82%). Effluent NH_4^+ concentration was always less than 1 mg N/L, and not affected by the aeration ratio, suggesting that aeration energy saving is feasible. The ORP and pH profiles indicate that the aerobic cycle can be controlled by a control point (ammonia valley) on the pH profile, which indicates the end of nitrification, and the anoxic cycle controlled by another point (nitrate knee) on the ORP profile, which indicates the end of denitrification.

A dual control strategy was, therefore, applied to another AAA system for terminating aerobic–anoxic periods and initiating anoxic–aerobic cycles. Specifically, the aerobic cycle is controlled by the inflection point on the dpH/d*t* profile and the anoxic cycle by the d^2ORP/dt^2 profile. With the control scheme used, the system performance is comparable to that produced by fixed f_a values, with concentrations of effluent NH_4^+ and NO_3^- of 1.6 and 3.6 mg N/L, respectively, and removal efficiencies for COD and TN of 84 and 80%, respectively. The energy saving (30 to 54%) is significant because the average f_a now reduces to 0.23 (air on–off = 0.65 hours/2.2 hours). Additionally, two constraints involving a minimum ORP (-120 mV) and a maximum anoxic duration (3 hours) were used to account for extremely high or low COD:TKN.

The present study is believed to simplify operation of the AAA system to maintain the effluent nitrogen discharge requirements and save significant aeration energy costs.

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