



Intercross real-time control strategy in alternating activated sludge process for short-cut biological nitrogen removal treating domestic wastewater

WANG Shuying^{1,*}, ZHANG Shanfeng^{1,2}, PENG chengyao¹, AKIO TAKIGAWA³

1. Key laboratory of Beijing water quality science and water environment recovery engineering, Beijing University of Technology, Beijing 100022, China. E-mail: wsy@bjut.edu.cn

2. Beijing Municipal Engineering Professional Design Institute Co. Ltd., Beijing 100037, China

3. Department of Civil and Environmental Engineering, Maebashi Institute of Technology 460-1, Kamisatory-cho, Maebashi, Gunma 371-0816, Japan

Received 5 October 2007; revised 21 November 2007; accepted 24 December 2007

Abstract

To develop technically feasible and economically favorable dynamic process control (DPC) strategies for an alternating activated sludge (AAS) system, a bench-scale continuous-flow alternating aerobic and anoxic reactor, performing short-cut nitrogen removal from real domestic wastewater was operated under different control strategies for more than five months. A fixed-time control (FTC) study showed that bending-points on pH and oxidation-reduction potential (ORP) profiles accurately coincided with the major biological activities. “Ammonia valley” on the pH profile represented the end of nitrification, whereas, the “nitrite knee” on the ORP profile and “nitrite apex” on the pH profile both indicated the end of denitrification. Therefore, a new reliable and effective real-time control strategy was developed using pH and ORP as control parameters, to improve the performance of the AAS process. The online control strategy could achieve up to 87% of the total nitrogen (TN) removal efficiency on an average, and saving approximately 20% aeration energy, as compared to the conventional steady-state control systems. Moreover, stable short-cut nitrification and denitrification were successfully achieved with an average nitrite accumulation ratio of above 95%.

Key words: alternating activated sludge process; continuous-flow; real-time control; nitrification

Introduction

The operation of wastewater treatment plants is challenging for many small communities, for economical and technical reasons. The strict effluent requirements defined by the China Environment Protection Bureau (GB18918-2002) (Ma and He, 2003), which came into effect in the year 2005, will probably have to increase both operation costs and economical penalties to avoid process failure. There are, therefore, strong incentives to upgrade the existing wastewater treatment plants to have them cope with the future effluent standards.

The alternating activated sludge (AAS) process is one of the most commonly used processes, especially for small-sized treatment facilities. The process generally consists of a single aeration basin configuration in which oxygen is either supplied by surface turbines or diffusers. During switched-on periods, ammonium is converted into a nitrate which is subsequently used to remove organic carbon in the switched-off periods. An important feature of the alternating AAS process is its flexible control ability, which makes it suitable for optimization of operating costs (Hyunook *et al.*, 2000); however, there are two major

operational difficulties, which are the timings to initiate aerobic or anoxic periods and the duration of those periods. The aerobic periods must be long enough to allow the generation of an adequate amount of nitrate for subsequent endogenous nitrate respiration (ENR), but not too long considering the energy and pH consumption. Similarly, the anoxic periods must be allowed to proceed long enough to use up the available nitrate, but not too long to generate the undesirable anaerobic conditions. Conventional AAS operations of wastewater treatment application steady-state control schemes have always led to poor system performance and unnecessary resource consumption (Al-Ghusain *et al.*, 1995; Hao *et al.*, 1991; Vassos, 1993b). Thus, the need for a reliable AAS process control strategy is apparent.

Oxidation-reduction potential (ORP) and/or pH have been reported to be reliable and practical for real-time control of wastewater treatment in terms of both removal efficiency and cost (Akin and Ugurlu, 2005; Chapentier *et al.*, 1998; Fuerhacker *et al.*, 2000; Kim and Hao, 2001; Kishida *et al.*, 2003; Kim *et al.*, 2004; Lo *et al.*, 1994; Plisson-Saune *et al.*, 1996; Peng *et al.*, 2002; Peng *et al.*, 2006; Puig *et al.*, 2006). Previous researchers have identified the “nitrate knee” in ORP profiles and the “nitrate apex” in pH profiles, which indicate the end of

* Corresponding author. E-mail: wsy@bjut.edu.cn.

denitrification (Al-Ghusain *et al.*, 1995; Koch and Oldham, 1985), and the “nitrogen break point” or the “DO elbow” in ORP profiles and the “ammonia valley” in pH profiles, which indicate the end of nitrification (Al-Ghusain *et al.*, 1994; Wareham *et al.*, 1994;). Therefore, under real-time operation, these control points can indicate the duration of each aerobic or anoxic phase cycle to optimize the performance of AAS process.

Real-time control strategy based on ORP and/or pH has achieved much progress on traditional biological nitrogen removal, from different kinds of wastewaters (Kim and Hao, 2001; Kim *et al.*, 2004). Unfortunately, few studies have used both indicators (pH and ORP) to investigate the short-cut nitrogen removal process control in treating real domestic wastewater in AAS systems.

Short-cut nitrogen removal requires the inhibition of nitrite oxidizing bacteria (NOB) activities without affecting ammonia oxidizing bacteria (AOB), which results in the ammonia oxidation rate exceeding the rate of nitrite oxidation. Therefore, nitrogen removal would occur via the nitrite pathway ($\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{N}_2$) with a much lower (40%) carbon source demand for denitrification and a significantly lower (25%) oxygen requirement for nitrification. It is particularly favorable for nitrogen removal from domestic wastewaters with a low C/N ratio.

This study was therefore undertaken to investigate the feasibility of using pH and ORP as control parameters under short-cut nitrification-denitrification conditions and to establish a more effective and reliable real-time control strategy for AAS systems. Specifically, the objectives are to: (1) identify features on the ORP and pH profiles that could be used for short-cut nitrogen removal control; (2) investigate the use of ORP and pH as control parameters for the AAS system under different control conditions; and (3) observe the effects of different control strategies on domestic wastewater treatment in terms of power saving, nitrogen removal, and sludge characteristics.

1 Materials and methods

1.1 Experimental equipments

The schematic diagram and profile chart of the AAS system are presented in Figs.1 and 2, respectively. The system has a concentric cylinder shared by a settler (54 L), an anaerobic zone (14 L) as the external section, and the 32 L AAS reactor as the internal section. Saturated air was used for aeration and mixing in the reactor during air-on periods. Additional mixing in the reactor during air-off periods was provided by an agitator. The system was continuously monitored via ORP (340i, WTW, Germany), DO (340i, WTW, Germany), and pH (730i, WTW, Germany,) probes. The probes were cleaned and calibrated once a

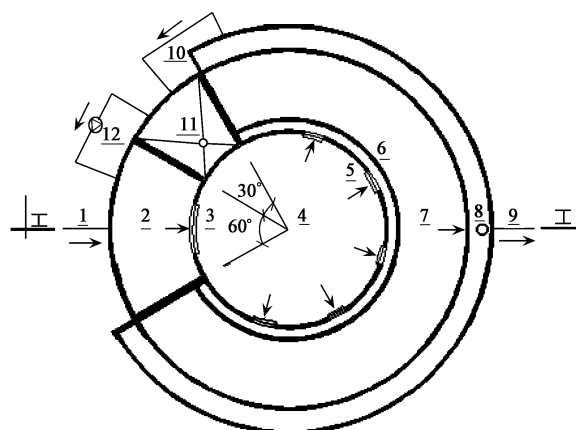


Fig. 1 Schematic diagram of the alternating activated sludge (AAS) system. (1) feed pipe; (2) anaerobic zone; (3) and (5) flow director windows; (4) aerobic/anoxic zone; (6) flow board; (7) settler; (8) overflow weir; (9) effluent pipe; (10) sludge return; (11) anoxic zone; (12) return pipe.

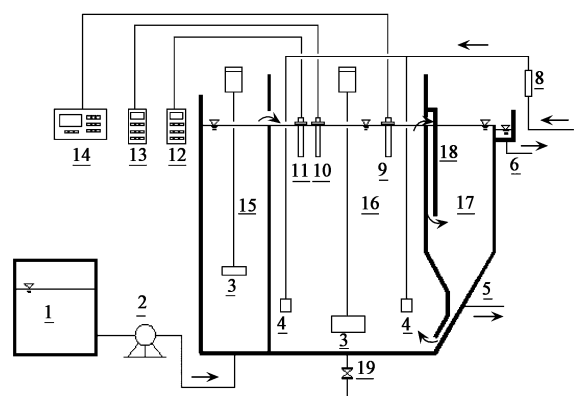


Fig. 2 I-I profile chart of the AAS system. (1) feed tank; (2) feed pump; (3) agitator; (4) air diffuse; (5) sludge return; (6) effluent; (7) air-source; (8) air flow meter; (9) and (14) pH meter; (10) and (13) ORP meter; (11) and (12) DO meter; (15) anaerobic zone; (16) aerobic/anoxic zone; (17) settler; (18) flow director; (19) aeration pipe.

week and shown 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) as well as for setting the air on and off.

1.2 Wastewater and sludge

Raw wastewater was collected from a septic tank in the campus residence of the Beijing University of Technology, China. The typical characteristics of the wastewater were summarized in Table 1. The activated sludge in the system was seeded from an anoxic-oxic (A/O) reactor, which had stable operation and nutrient removal.

Table 1 Typical characteristics of raw domestic wastewater

	COD _{Cr} (mg/L)	BOD ₅ (mg/L)	TKN (mg/L)	NH ₄ ⁺ -N (mg/L)	pH	Alkalinity (CaCO ₃ mg/L)
Range	160–500	85–290	60–110	50–100	7.0–8.0	480–520
Average	310	120	70	65	7.5	490

TKN: total Kjeldahl nitrogen.

1.3 Analytical method

Samples for dynamic studies were collected directly from the reactor. Conventional parameters such as mixed liquor suspended solids (MLSS), COD_{Cr} , total Kjeldahl nitrogen (TKN), $\text{NH}_4^+\text{-N}$, $\text{NO}_2^-\text{-N}$, $\text{NO}_3^-\text{-N}$, and alkalinity were routinely analyzed according to the standard methods (APHA, 1995). Multi N/C 3000 (Jena, Germany) and 861 advanced compact IC (Metrohm, Switzerland) were used in the analysis of wastewater samples.

1.4 Experimental procedure

Two sets of experiments were carried out for different purposes. One was designed to evaluate a fixed-time operation, of which the control process was carried out under different total cycle time (t_c) and aeration time ration (f_a). The objective of the fixed-time study mainly focused on tracing the ORP and pH variations during the process and the relationship between pH, ORP, and water quality. The other set of the experiment was designed to evaluate the real-time operation via the indication of ORP and pH. In real-time control experiments, the system was operated under different F/M ratios and was subjected to nitrogen and flow-shock loading. The experimental procedure and conditions are summarized in Table 2.

2 Results and discussion

2.1 Startup of nitrification under low DO concentration

Nitrite accumulation can be accomplished via selective NOB inhibition at low DO concentration (Kuai and Verstraete, 1998), which is attributed to the different saturation coefficients for DO between AOB and NOB. According to double Monod kinetics, the half-saturation constants for DO were reported to be 0.25–0.5 mg/L for AOB and 0.72–1.84 mg/L for NOB (Randall *et al.*, 1992), respectively. Consequently, the oxidation of nitrite to nitrate was inhibited at a low DO concentration, but not for the oxidation of ammonia to nitrite. The reactor was operated for 35 d under 0.5 mg/L DO concentration until stable partial nitrification and denitrification were achieved. The nitrite accumulation rate and the ammonia removal efficiency reached about 85%–90% and 90% respectively.

Table 2 Experimental procedure and conditions

Parameter	Startup	Fixed-time control	Real-time control
Control pattern*	120 vs. 120 ($f_a=0.5$)	(I) 120 vs. 120 ($f_a=0.5$) (II) 90 vs. 90 ($f_a=0.5$) (III) 110 vs. 70 ($f_a=0.61$) (IV) 140 vs. 100 ($f_a=0.58$)	Variable
DO (mg/L)	0.5	2.5–3.0	2.5–3.0
Temp. (°C)	22±2	22±2	22±2
HRT (h)	10–12	10–12	10–12
SRT (d)	15–20	15–20	15–20
MLSS (mg/L)	5,500	5,500	5,500

* Air-on time vs. Air-off time. Aeration time ration (f_a)= total aeration time in one cycle/length of one cycle. HRT: hydraulic retention time; SRT: sludge retention time; MLSS: mixed liquor suspended solids.

2.2 Fixed-time control study

Figure 3 presents the typical cycle of the ORP and pH profiles along with the nitrogen dynamic profiles under 140–100 (140 min air-on–100 min air-off) fixed-time operation. The ORP profile exhibited a two-stage increase in the aerobic condition. At the start of air-on, ORP increased sharply because of the introduction of dissolved oxygen by aeration. Then ORP increased gradually till the end of the aeration phase, without showing any characteristic points. Therefore, ORP could not be used as an effective real-time control parameter of nitrification. A slight increase of $\text{NO}_2^-\text{-N}$ concentration was noted after the disappearance of $\text{NH}_4^+\text{-N}$ during the aeration periods, which was caused by further oxidation of the new, incoming $\text{NH}_4^+\text{-N}$. Because of the release of the hydrogen ion from nitrification and consumption of alkalinity, the pH dropped rapidly till the nitrification ended (point B, ammonia valley), after which it rose slowly until the end of aeration on account of CO_2 stripping.

During the air-off period, the ORP remained stable during the transient because of the remaining dissolved oxygen (DO); thereafter, the ORP dropped drastically because of anoxic denitrification. An obvious breakpoint (point F) appeared on the ORP profile when the concentration of the nitrite dropped to zero. The breakpoint was named as the “nitrate knee” in the traditional nitrogen removal process (in this study, it should be “nitrite knee”). Furthermore, during the anoxic stage, pH increment terminated at the end of denitrification, which corresponded with point C. This was caused by the production of OH^- from denitrification and the recovery of alkalinity. Subsequently, pH decreased because of the formation of fatty acid, which indicated that the system shifted into biological anaerobic respiration conditions. The bending-point on the pH profile, which occurred at the same time as the “nitrate knee”, was termed as “nitrate apex” in the traditional nitrogen removal process (In this study, it should be “nitrite apex”). Thus, both point G and C could indicate the end of the denitrification.

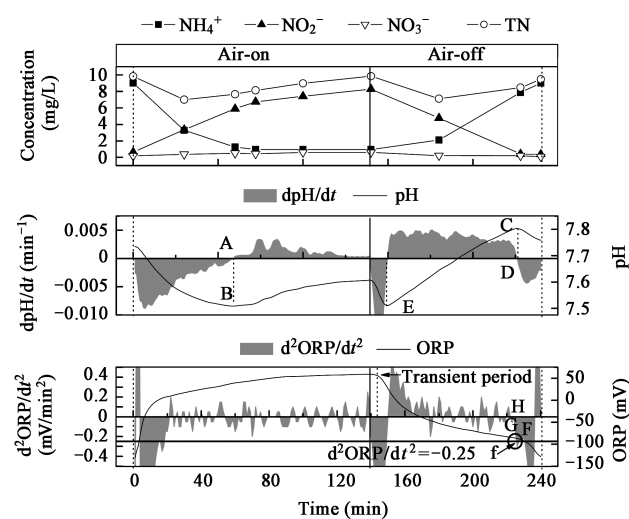


Fig. 3 Typical nitrogen dynamic with oxidation reduction potential (ORP) and pH under fixed-time control.

2.3 Real-time control strategy based on the feature points of ORP and pH profiles

The results of the fixed-time study showed that both ORP and pH could be applied to control the AAS system, in particular, the “ammonia valley” on the pH profile for nitrification, and the “nitrite apex” on the pH profile and the “nitrite knee” on the ORP profile for denitrification. However, the application of derivatives is more convenient than their absolute values, to judge the feature points, when implementing online operation.

In Fig.3, from beginning to point A, where $dpH/dt = 0$, the value of dpH/dt changed from negative to positive, which could be used to determine the end of nitrification. From point D to end in the air-off stage, where the change of dpH/dt was opposite to the period of point A, could be used to determine the end of denitrification. However, point H on the d^2ORP/dt^2 profile in the air-off stage, where $d^2ORP/dt^2 = 0$, could not be used to determine the end of denitrification because of the monitoring noises on the probes. To prevent erroneous process control, a limit value of $d^2ORP/dt^2 = -0.25$ mV/min (point F) was set as the control value of ORP, to reflect the denitrification condition in the real-time control system.

2.4 Operation constraints

Besides being highly susceptible to monitoring noise fluctuations, real-time control strategies with dynamic influent and complex wastewater treatment systems still need to apply operation constraints as emergency control, whenever characteristic points cannot be detected by the controllers (Chachuata *et al.*, 2005; Lo *et al.*, 1994; Thomann *et al.*, 2002).

When influent COD_{Cr}/TKN ratio is high, ORP readings fall rapidly without the “nitrate knee” being detected (Kim and Hao, 2001). Therefore, a constraint of ORP profile must be selected to initiate aeration. From all the ORP profiles obtained from the present study, an ORP constraint value of -120 mV can be used. When influent COD_{Cr}/TKN ratio is low, the anoxic period may be too long to ensure complete denitrification because the NO_2^- endogenous respiration rate is too slow. Complete NO_2^- removal in this case may result in excessive accumulation of NH_4^+ during the sequent aerobic period, which will lead the system into aggravating cycles. It is reasonable to set a maximum of 150 min constraint for the denitrification period. Real-time strategy will fail to function if the alkalinity is scarce for fulfilling ammonia oxidation because the “ammonia valley” on the pH profile cannot be detected. Hence it is suitable to set a maximum aeration time of 250 min for the nitrification period. The proposed system is only applicable to complete a mixed scheme. Occasionally, undesirable disturbances will stimulate the probes to give fake signals, which result in the untimely termination of nitrification or denitrification to the system. Therefore, a minimum retention time of 20 min is preset, to ensure basic nitrification or denitrification, to prevent NH_4^+ or nitrite overloading in the subsequent reactor cycles.

2.5 Designation of real-time control strategy

The real-time control strategy presented in Fig.4 requires a calculation of a moving average of pH-ORP data to filter noises. During the aerobic period, the dpH/dt profile is monitored to detect the “ammonia valley” where $dpH/dt = 0$. The aeration was actually prolonged for 10 min after the detection of the “ammonia valley”, to ensure complete ammonia removal. When the air was turned off, the end of denitrification will be determined by the correlated breakpoints on pH and ORP profiles. An additional 5 min was introduced after the detection of the breakpoints on the pH and ORP profiles, to ensure complete denitrification. During the online control process, if any one of the breakpoints appear, the control procedure will counter-check pH or ORP preset value and preset time, to verify whether the control point has been met.

2.6 Typical cycles under real-time control

Figure 5 presents the typical dynamic studies of different nitrogen species in effluents under real-time control. The control scheme worked steadily and the features described earlier were well defined. Air-on or air-off was well implemented according to the control strategy shown in Fig.4.

2.7 Operation performance under influent shock-loading

To ensure that the control strategy was able to handle variable conditions, the system was subjected to influent flow and nitrogen shock loadings. Results showed that the real-time control operation had a great ability to accommodate influent shock loadings.

Figure 6a shows the pH and ORP profiles under hydraulic shock loading of the system (130% of the normal flow-rate). All critical control points including “ammonia valley”, “nitrite knee”, and “nitrite apex” were detected. The control strategy was applied to allow prolonged nitrification and the composition of the effluent collected before and after the shock loading did not vary significantly.

Figure 6b presents the results of influent ammonia shock loading (120% the normal influent ammonia concentration). Both aerobic and anoxic durations were extended to remove all the influent NH_4^+ and NO_2^- generated from nitrification. The prolonged anoxic duration caused excessive NH_4^+ accumulation in the system, which resulted in higher effluent nitrogen. Although the composition of the effluent collected after the shock loading showed rather high NH_4^+ (7 mg/L) and NO_2^- (5 mg/L) concentrations, the system was able to recover once additional ammonia loading was terminated.

2.8 Overall performance under different control strategies

The average contaminant concentrations of different phases and the corresponding sludge characteristic changes of the reactor, during the entire study period, under fixed-time schemes and real-time schemes are presented in Table 3.

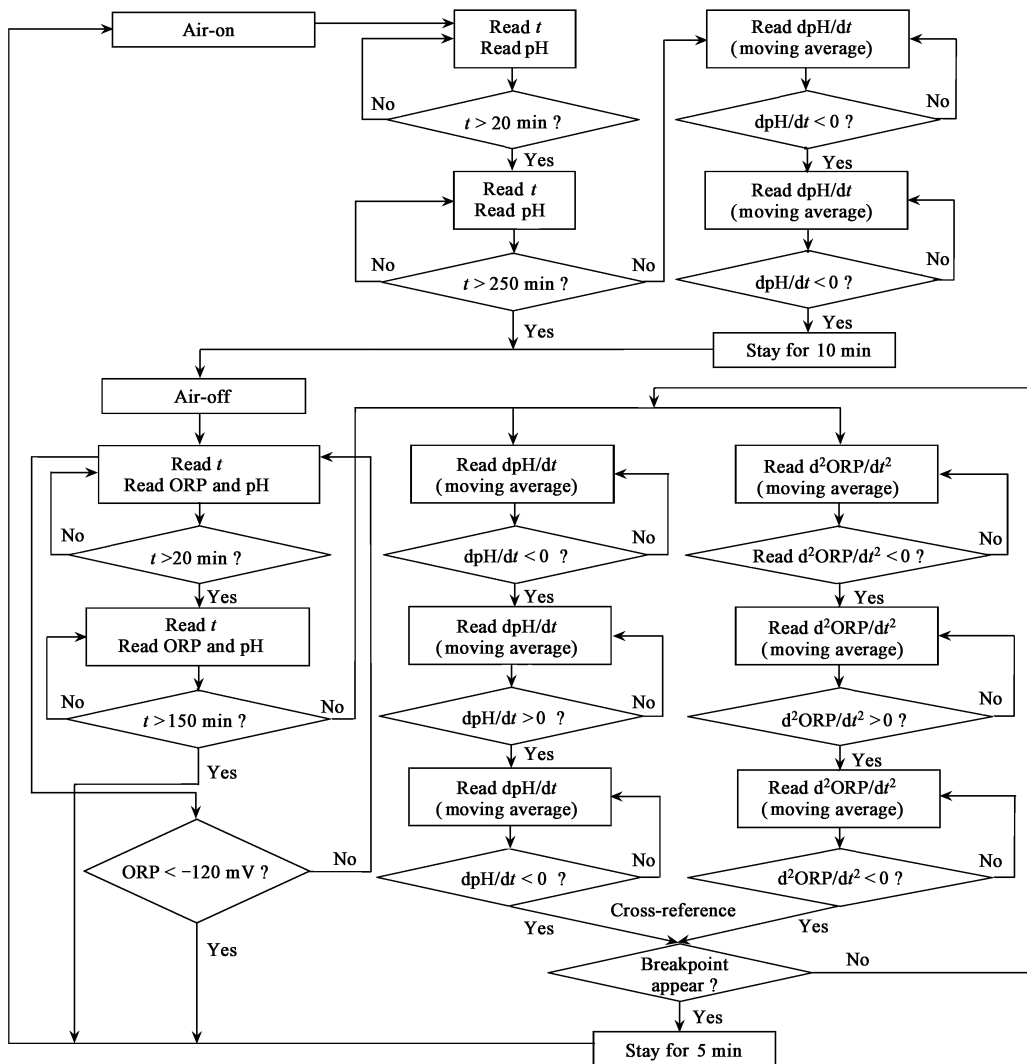
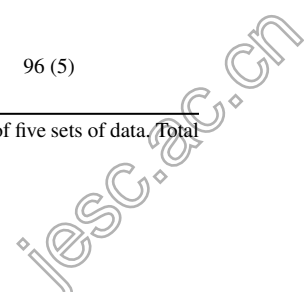


Fig. 4 Flow chart for the real-time control strategy.

Table 3 Overall performance of the AAS system at different phases

Parameter	Wastewater				Sludge character		f_a	Nitrite accumulation ratio (%)
	COD _{Cr} (mg/L)	TN (mg/L)	NH ₄ ⁺ (mg/L)	NO ₂ ⁻ (mg/L)	MLSS (mg/L)	SVI (ml/g)		
Phase I (120 min air-on vs. 120 min air-off)								
Influent	203 (50)	72 (5)	68 (6)	0.2 (0.1)				
Effluent	34 (3)	14 (3)	3 (0.8)	11 (4)	5,726 (52)	141 (1.4)	0.5	75 (11)
Removal	83%	81%	96%	–				
Phase II (90 min air-on vs. 90 min air-off)								
Influent	318 (26)	70 (2)	65 (3)	0.1 (0.1)				
Effluent	46 (6)	11 (3)	5 (2)	6 (1)	5,652 (60)	142 (14)	0.5	87 (2.8)
Removal	86%	84%	92%	–				
Phase III (110 min air-on vs. 70 min air-off)								
Influent	386 (40)	66 (4)	63 (5)	0.1 (0.1)				
Effluent	36 (5)	12 (4)	3 (3)	9 (5)	5,365 (50)	149 (9)	0.61	90 (20)
Removal	91%	82%	95%	–				
Phase IV (140 min air-on vs. 110 min air-off)								
Influent	309 (49)	69 (8)	65 (6)	0.2 (0.5)				
Effluent	45 (7)	11 (5)	4 (3)	7 (5)	5,612 (40)	141 (10)	0.58	90 (15)
Removal	85%	84%	94%	–				
Phase V (real-time)								
Influent	353 (80)	75 (4)	73 (4)	0.1 (0.1)				
Effluent	41 (6)	10 (5)	4 (1)	6 (1)	5,725 (42)	106 (6)	0.47	96 (5)
Removal	88%	87%	95%	–				

HRT 10 h, SRT 20 d. Reaction temperature 22±2°C. Values in brackets represent standard deviation. Data based on the average of five sets of data. Total cycle time (t_c) and f_a under real-time are variable. SVI: sludge volume index.



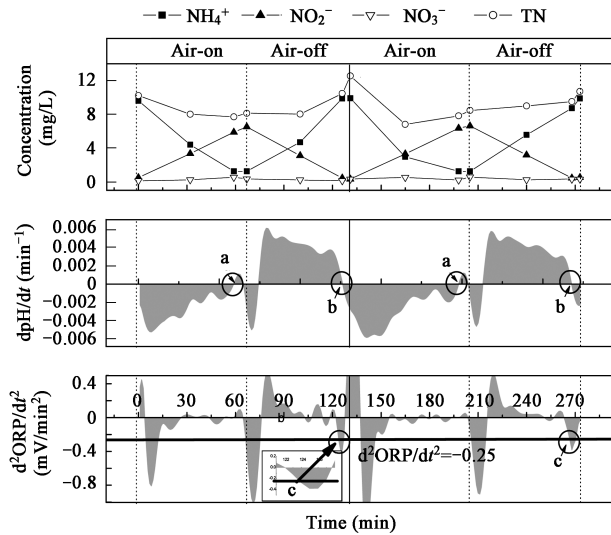


Fig. 5 Dynamics of NH_4^+ , NO_2^- , NO_3^- concentrations, and ORP, pH profiles of the real-time control.

The influent concentration fluctuated between 150 and 500 mg/L COD_{Cr} , whereas, the effluent COD_{Cr} concentration remained low and stable (less than 50 mg/L). The average COD_{Cr} removal efficiency was higher than 80% in all five phases, which showed that the operation mode had little impact on COD_{Cr} removal.

Similarly, perfect nitrogen removal efficiency (more than 80%) was accomplished in five phases. The average effluent TN was less than 15 mg/L. Under the real-time control pattern, in particular, an average of 87% TN removal efficiency was achieved, which showed that the system had a greater ability to accomplish nitrogen removal compared with steady-state control operations.

The aeration cost was approximately reduced by 20%, by using the real-time control operation, with a typical average f_a of 0.47, compared to the fixed-time control f_a values of 0.5, 0.58, or 0.61. Additionally, average sludge volume index (SVI) also dropped from 141 to 106 ml/g, which indicated the improvement of activated sludge settle ability.

It was believed that the nitrite pathway was achieved by

a successful NOB wash out in phase V. In any particular reactor cycle, nitrite oxidation would naturally start upon the completion of ammonia oxidation. Thus, starting the anoxic period upon the completion of ammonia oxidation resulted in the accumulated nitrite being denitrified immediately afterward. This restricted the energy source for the NOB and therefore limited its growth, which led to 96%, and an even higher nitrite accumulation rate in the subsequent cycles, under real-time control operation.

3 Conclusions

A bench-scale AAS system was operated for more than five months to evaluate the effects of different time-control schemes on the system performance, and to develop a feasible if not more reliable real-time control strategy using pH and ORP as control parameters, which was expected to optimize the operation of the AAS system to achieve the effluent discharge requirement and save aeration energy costs significantly. It delivered promising and practical control information for full-scale biological wastewater treatment processes.

It was demonstrated that real-time control was an effective control strategy to accomplish short-cut nitrogen removal based on a successful reactor startup. An average nitrite accumulation ratio of 96% in this case was achieved under the real-time control. However, a systematic, fundamental study to understand how AOB and NOB were selected, for or against, in such biological wastewater treatment systems, and how bacterial properties were influenced by plant design and operation, is yet to be carried out.

Acknowledgements

This work was supported by the Beijing Science and Technology Committee Match Project of “863 Plan” (No. Z0005186040421), the International Cooperative Programs of Beijing Science and Technology Committee, and the Project of Funding Project for Academic Human Resources Development in Institutions of Higher Learn-

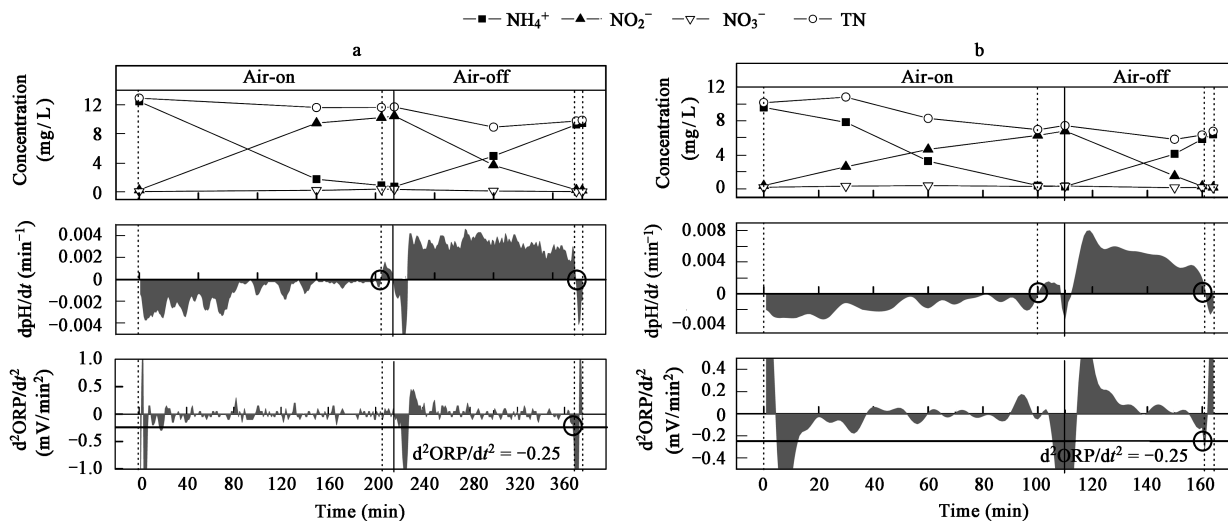


Fig. 6 Variation of nitrogen concentration, pH, and ORP profiles of the real-time control of 130% hydraulic (a), 120% ammonia (b) shock loading.

jesec.cn

ing under the Jurisdiction of Beijing Municipality (PHR (IHLB)).

References

- Akin B S, Ugurlu A, 2005. Monitoring and control of biological nutrient removal in a Sequencing. *Batch Reactor Process Biochemistry*, 40: 2873–2878.
- Al-Ghusain I A, Huang J, Hao O J, Lim B S, 1994. Using pH as a real time control parameter for wastewater treatment and sludge digestion process. *Water Sci Tech*, 30(4): 159–168.
- Al-Ghusain I A, Oliver J, Hao O J, 1995. Use of pH as control parameter for aerobic/anoxic sludge digestion. *J Environ Eng*, 121(3): 225–235.
- APHA (American Public Health Association), 1995. Standard Methods for the Examination of Water and Wastewater. 19th ed. Washington DC, USA: American Public Health Association/American Water Works Association/Water Environment Federation.
- Chachuata B, Rocheb N, Latifia M A, 2005. Long-term optimal aeration strategies for small-size alternating activated sludge treatment plants. *Chemical Engineering and Processing*, 44: 593–606.
- Chapentier J, Martin G, Wacheux H, Gilles P, 1998. ORP regulation and activated sludge: 15 years of experience. *Water Sci Technol*, 38 (3): 197–208.
- Fuerhacker M, Bauer H, Ellinger R, Sree U, Schmid H, Zibuschka F, Puxbaum H, 2000. Approach for a novel control strategy for simultaneous nitrification/denitrification in activated sludge reactors. *Water Res*, 34(9): 2499–2506.
- Hao O J, Kim M H, Al-Ghusain I A, 1991. Alternating aerobic and anoxic digestion of waste activated sludge. *J Chem Technol Biotechnol*, 52(4): 457–472.
- Hyunook K, McAvoy T J, Anderson J S, Hao O J, 2000. Control of an alternating aerobic-anoxic activated sludge system-Part 2: optimization using a linearized model. *Contr Eng Pract*, 8: 279–289.
- Kim H, Hao O J, 2001. pH and oxidation-reduction potential control strategy for optimization of nitrogen removal in an alternating aerobic-anoxic system. *Water Environ Res*, 73(1): 95–102.
- Kim J H, Chen M, Kishida N, Sudo R, 2004. Integrated real-time control strategy for nitrogen removal in swine wastewater treatment using sequencing batch reactors. *Water Res*, 38: 3340–3348.
- Kishida N, Kim J H, Chen M, Sasaki H, Sudo R, 2003. 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(3): 285–290.
- Koch F A, Oldham W K, 1985. Oxidation-reduction potential—a tool for monitoring, control and optimization of biological nutrient removal system. *Water Sci Technol*, 17: 259–281.
- Kuai L, Verstraete W, 1998. Ammonium removal by the oxygen limited autotrophic nitrification-denitrification system. *Appl Environ Microbiol*, 64: 4500–4506.
- Lo C K, Yu C W, Tam N F Y, Traynor S, 1994. Enhanced nutrient removal by oxidation-reduction potential (ORP) controlled aeration in a laboratory scale extended aeration treatment system. *Water Res*, 28(10): 2087–2094.
- Ma S H, He X H, 2003. Brief on the pollutant discharge standard of municipal wastewater treatment plant. *Water and Wastewater*, 29(9): 89–94.
- Peng Y Z, Gao J F, Wang S Y, Sui M H, 2002. Use pH and ORP as fuzzy control parameters of denitrification in SBR process. *Water Sci Technol*, 46(4-5): 131–137.
- Peng Y Z, Ma Y, Wang S Y, 2006. Improving nitrogen removal using on-line sensors in the A/O process. *Biochemical Engineering Journal*, 31: 48–55.
- Plisson-Saune S, Capdeville B, Mauret M, Deguin A, Baptiste P, 1996. Real-time control of nitrogen removal using three ORP bending points: signification, control strategy and results. *Water Sci Technol*, 33(1): 275–280.
- Puig S, Corominas L, Traore A, Colomer J, Balaguer M D, Colprim J, 2006. An on-line optimisation of a SBR cycle for carbon and nitrogen removal based on on-line pH and OUR: the role of dissolved oxygen control. *Water Sci Technol*, 53(4-5): 171–178.
- Randall C W, Barnard J L, Stensel H D, 1992. Design and retrofit of wastewater treatment plants for biological nutrient removal. *Water Quality Management Library*, 5: 25–26.
- Thomann M, Rieger L, Frommhold S, Siegrist H, Gujer W, 2002. An efficient monitoring concept with control charts for on-line sensors. *Water Sci Technol*, 46(4-5): 107–116.
- Vassos T D, 1993b. Future direction in instrumentation, control and automation in the water and wastewater industry. *Water Sci Technol*, 28(11-12): 9–14.
- Wareham D G, Marvinic D S, Hall K J, 1994. Sludge digestion using ORP regulated aerobic anoxic cycles. *Water Res*, 28(2): 373–384.