Chemical Engineering Journal 151 (2009) 195–201

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Optimization of anoxic/oxic step feeding activated sludge process with fuzzy control model for improving nitrogen removal

Guibing Zhu[a,b], Yongzhen Peng[b,c,*], Bin Ma[b], Yu Wang[a], Chengqing Yin[a]

[a] State Key Laboratory of Environmental Aquatic Quality, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, PR China
[b] School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin, PR China
[c] Key Laboratory of Beijing Water Quality Science and Water Environment Recovery Engineering, Beijing University of Technology, Beijing, PR China

ARTICLE INFO

Article history:
Received 11 December 2006
Accepted 17 February 2009

Keywords:
Step feeding process
Biological nitrogen removal
Fuzzy control
Optimization

ABSTRACT

It has been proved that higher total nitrogen removal efficiency could be obtained in step feeding activated sludge process by adjusting the inflow rate distribution and the volume of each stage. But the optimization of the step feeding process would be complicated owing to adjustment of inflow rate and volume. To develop the auto-control and operational decision support system is an urgent and necessary work for well application of step feeding process. Although biological wastewater treatment, especially the biological nitrogen removal process, has the characteristics of complex nonlinear, it provides widespread opportunities for artificial intelligent control. In this paper a fuzzy control model of anoxic/oxic step feeding activated sludge process was developed under the condition of sufficient and insufficient influent carbon source. The detailed information on development of fuzzy model was addressed based on collecting and analyzing previous experimental data. The influent C/N ratio was selected as input variable and inflow rate and volume distribution in each stage were selected as output variables. Moreover, the calibration and application approaches of control model were also studied through pilot-scale experiments (1000 L/d) with domestic sewage. The highlight is that the method and approach of model calibration are well discussed so that it provides good opportunities on practical application. During three months experimental period enhanced total nitrogen removal efficiency of more than 95.1% was reached with the influent C/N ratio of 8.16–12.3, average of 9.78.

1. Introduction

The step feeding anoxic/oxic activated sludge process has attracted much attention in recent years due to its high total nitrogen removal efficiency. Many researchers have studied the operation characteristics and parameters of step feeding process by theoretical analysis and computer simulation [1–3]. Some practical experiences were also drawn from extended, renewed or retrofitted conventional activated sludge process [4–8]. Previously on studies of Zhu et al. [9,10] high total nitrogen removal efficiency, higher than 95%, could be obtained in step feeding process by adjusting the inflow rate distribution and the volume in each stage. However, the optimum design and operation of the step feed process is a difficult task because of the reactor configuration and inflow rate distribution. Volume ratios of anoxic and aerobic volumes and wastewater fraction to be diverted from the inlet of the system are important parameters, and should be considered in design of the step feeding process. Wastewater characteristics, especially C/N ratios significantly affect the design [4,10]. So to develop the auto-control and operational decision support system is an urgent and necessary work for well application of step feeding process.

Although biological wastewater treatment, especial the biological nitrogen removal process, has the characteristics of complex nonlinear, it provide widespread opportunities for artificial intelligent control. Advances in control engineering suggest that hybrid control strategies, integrating some ideas and paradigms existing in different soft computing techniques, such as fuzzy logic and neural networks, may provide improved control performance in wastewater treatment processes [11]. Fuzzy control has become an important and effective tool for the development of such intelligent system [12]. During the last two decades, there were a variety of applications of fuzzy logic control in wastewater treatment plants to optimize operation and performance of bioprocesses. The control objective and parameters ranged from aeration [13–15], effluent suspended solid [16], external carbon addition [17], loading rate [18] to nitrification in Sequencing Batch Reactor (SBR) process [19] and dissolved oxygen concentration [20]. Zhu and Peng [21] reviewed the application and development of fuzzy control in urban wastewater treatment. However, there is no literature about optimization

* Corresponding author. Tel.: +86 10 62849307; fax: +86 10 62849307.
E-mail address: gbzhu@rcees.ac.cn (Y. Peng).

1385-8947/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.cej.2009.02.019

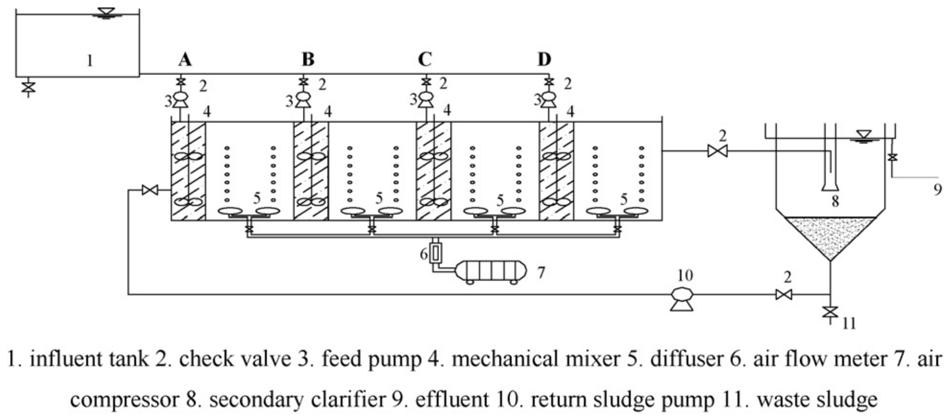

Fig. 1. Schematic diagram of anoxic/oxic step feeding activated sludge process system. (1) Influent tank, (2) check valve, (3) feed pump, (4) mechanical mixer, (5) diffuser, (6) air flow meter, (7) air compressor, (8) secondary clarifier, (9) effluent, (10) return sludge pump, and (11) waste sludge.

of anoxic/oxic step feeding activated sludge process with fuzzy control for improving nitrogen removal [10,11,21].

So the specific purpose of this research is to develop a fuzzy control model for optimization of step feeding process to improve biological nitrogen removal. Moreover, the calibration methods of control model for application in real sewage treatment plant were also verified and approved.

2. Materials and methods

2.1. Reactor configuration and experimental setup

The bench-scale reactor was well documented in literatures of [9] and [22]. The pilot-scale reactor was just magnified with the bench-scale. A two channels four feeds reactor was employed to simulate biological wastewater treatment based on step feeding process, as shown in Fig. 1. The dimension of cubic reactor made of plexiglass was 1400 mm × 460 mm × 600 mm. The aerobic and anoxic zones in each stage were separated by flashboards which are removable so as to adjust the volume ratio of anoxic zone and aerobic zone. The mechanical mixers were used in each anoxic zone to make the activated sludge and liquid mix well. A number of outlets for sampling were emplaced with distance from reactor bottom of 200 mm in each anoxic and aerobic compartment. The airflow rate was controlled by airflow meter for adjusting dissolved oxygen (DO) concentration in aerobic zone. An upright clarifier with a working volume of 125 L was employed for solid–liquid separation. The flow rates of influent, internal cycle and retuned sludge were controlled by peristaltic pumps (Lange Z2515-300 M, China) respectively.

Table 1
The distribution of volume and influent flow rate in each stage.

λ	Influent COD	Stage A			Stage B			Stage C			Stage D		
		Influent flow rate[a]	Volume[b]	Anoxic volume[c]	Influent flow rate[a]	Volume[b]	Anoxic volume[c]	Influent flow rate[a]	Volume[b]	Anoxic volume[c]	Influent flow rate[a]	Volume[b]	Anoxic volume[c]
1.00	256	25.00	29.38	10.64	25.00	25.00	25.00	25.00	23.75	26.32	25.00	21.88	28.57
1.25	292	33.87	31.25	16.00	27.10	25.00	25.00	21.68	23.12	27.02	17.34	20.62	30.30
1.50	335	41.53	33.75	12.96	27.69	25.00	25.00	18.46	21.25	29.41	12.30	20.00	31.25
1.75	360	47.97	37.50	10.00	27.41	25.00	25.00	15.66	21.25	29.41	8.95	16.25	38.46
2.00	385	53.20	41.25	9.09	26.60	26.25	23.80	13.30	16.87	37.03	6.67	15.00	37.50
2.25	432	57.81	42.50	7.35	25.69	26.25	23.81	11.42	17.50	32.14	5.08	13.12	38.09
2.50	460	61.57	45.62	6.84	24.63	25.00	25.00	9.85	17.50	32.14	3.94	11.87	42.10
2.75	495	64.76	48.75	6.41	23.55	25.00	27.50	8.56	16.25	34.61	3.11	10.00	45.71
3.00	530	67.50	51.25	4.88	22.50	23.75	31.58	7.50	15.63	34.00	2.50	9.38	46.67
3.50	597	71.90	57.50	4.07	20.54	21.25	38.23	5.87	13.75	36.36	1.67	8.75	42.85
4.00	656	75.29	60.62	3.60	18.82	19.37	45.16	4.70	12.50	37.50	1.17	8.12	38.46

[a] Influent flow rate in each stage was expressed as the percent of total flow rate.
[b] Volume in each stage was expressed as the percent of total volume.
[c] Anoxic volume in each stage was expressed as the percent of total volume in each stage.

Table 2
Fuzzy control rules.

Rule		C/N ratio		λ		V_1		V_2		V_3		V_4		V_{1A}		V_{2A}		V_{3A}		V_{4A}
1	IF	L	Then	L	And	L	And	L	And	H	And	H	And	H	And	L	And	L	And	L
2	IF	ML	Then	ML	And	ML	And	ML	And	MH	And	MH	And	MH	And	ML	And	ML	And	ML
3	IF	M	Then	M	And	M	And	M	And	M	And	M	And	M	And	M	And	M	And	M
4	IF	MH	Then	MH	And	MH	And	MH	And	ML	And	ML	And	ML	And	MH	And	MH	And	MH
5	IF	H	Then	H	And	H	And	H	And	L	And	L	And	L	And	H	And	H	And	H

λ: Inflow rate distribution ratio; V_1: volume of first stage; V_2: volume of second stage; V_3: volume of third stage; V_4: volume of fourth stage; V_{1A}: volume of anoxic zone in first stage; V_{2A}: volume of anoxic zone in second stage; V_{3A}: volume of anoxic zone in third stage; V_{4A}: volume of anoxic zone in fourth stage; L: low; ML: moderate low; M: moderate; MH: moderate high; H: high.

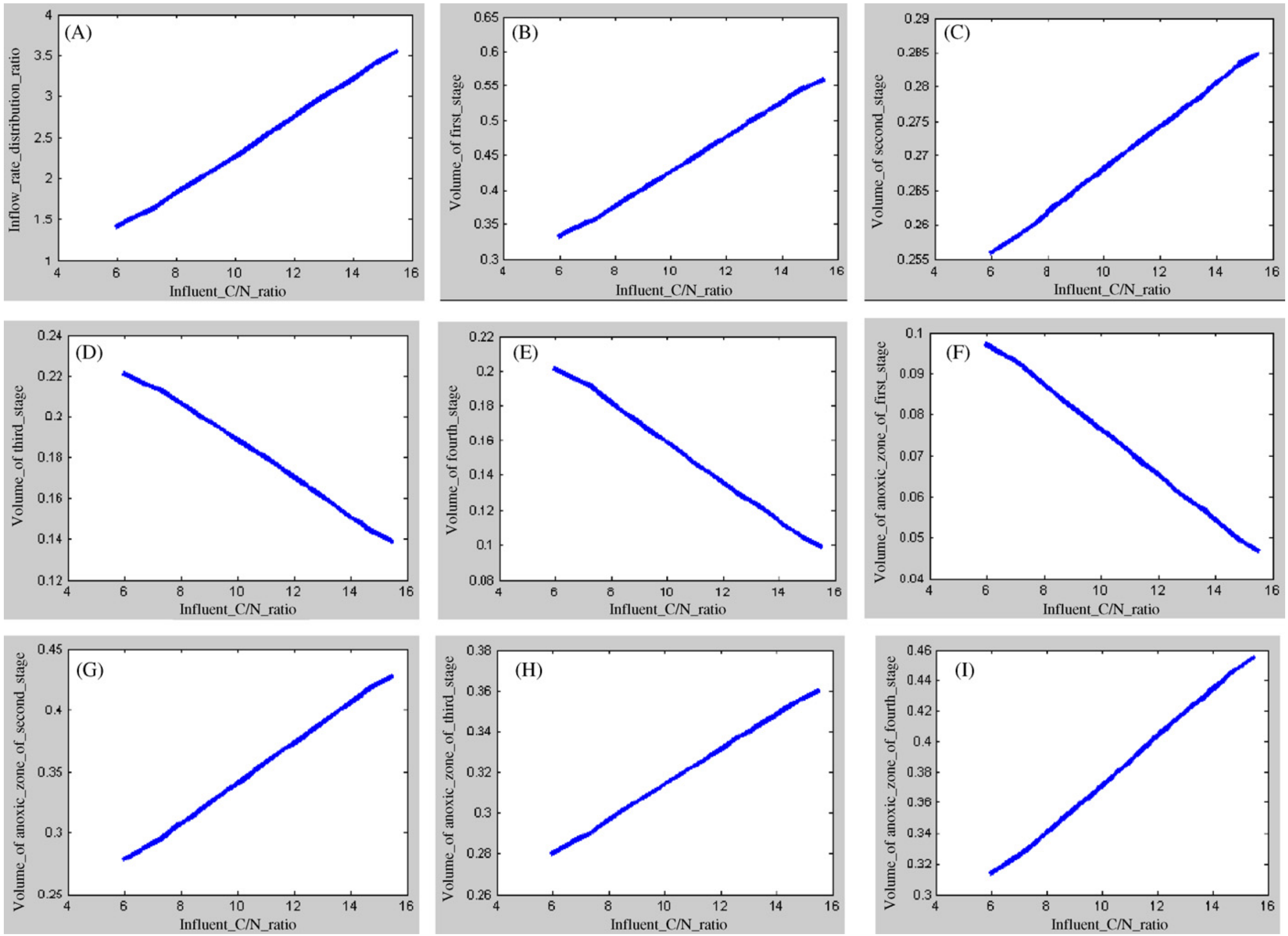

Fig. 2. Input and output curves of fuzzy optimize control model. (A) Influent C/N ratio versus influent flow distribution ratio; (B) influent C/N ratio versus volume of first stage; (C) influent C/N ratio versus volume of second stage; (D) influent C/N ratio versus volume of third stage; (E) influent C/N ratio versus volume of fourth stage; (F) influent C/N ratio versus volume of anoxic zone of first stage; (G) influent C/N ratio versus volume of anoxic zone of second stage; (H) influent C/N ratio versus volume of anoxic zone of third stage; (I) influent C/N ratio versus volume of anoxic zone of fourth stage.

2.2. Wastewater composition

The wastewater in bench-scale studies was synthesized described in literature [9] and [22]. The wastewater fed into the pilot-scale step feeding process was pumped from a cesspool in habitation district of Beijing University of Technology. The main wastewater characteristics are shown as follows: COD (258–440 mg/L), NH_4^+-N (29–48 mg/L), NO_2^--N (0–0.128 mg/L), NO_3^--N (0–0.9 mg/L) and TKN (33–51 mg/L).

2.3. Experimental operating procedure

In pilot study, activated sludge was collected from a wastewater treatment plant (AAO process) for inoculation. The start-up of step feeding process was initiated with cesspool wastewater. While the reactor was operated for 3.5 days in a batch mode to provide the initial colonization and accumulation of microorganisms, and then operated in a continuous flow mode gradually. Steady state was reached after 10 days. During the bench and pilot study period, SRT was controlled at 18 days using hydraulic control approach [23]. The sludge return rate was set at 0.5 time of total influent flow rate.

2.4. Sampling and analytical procedures

The parameters measured included pH, temperature, DO, COD, NH_4^+-N, NO_2^--N, NO_3^--N, mixed liquor suspended solids (MLSS), sludge volumetric index (SVI) and total nitrogen (TN). Samples were prepared after being filtered with 0.45 μm Whatman filter papers. All analyses were performed according to the Standard Methods [24]. The DO, pH and temperature were determined daily using WTW pH/Oxi 340i (Germany).

3. Result and discussion

3.1. Brief summary of previous research results

The previous research showed that the step feeding process with the influent flow distribution of 2.0:2.1:2.5:3.4 could improve total nitrogen removal efficiency significantly with optimal carbon source utilization when the influent C/N ratio was less than 4.91 [22]. So it is easy to optimize the process under this condition. In this paper we mainly addressed the optimization under high C/N ratios.

In the bench-scale experimental course the optimal operation and performance were achieved by adjusting inflow rate distribution and volume in each stage according to influent C/N ratio [9,22]. The total nitrogen removal efficiency of the step feeding process was a function of influent flow rate distribution ratio (λ), whereas the maximal inflow rate distribution ratio (λ_{max}) was determined by the influent C/N ratio. The optimal volume of each stage could be determined according to the influent flow distribution, as shown in Table 1.

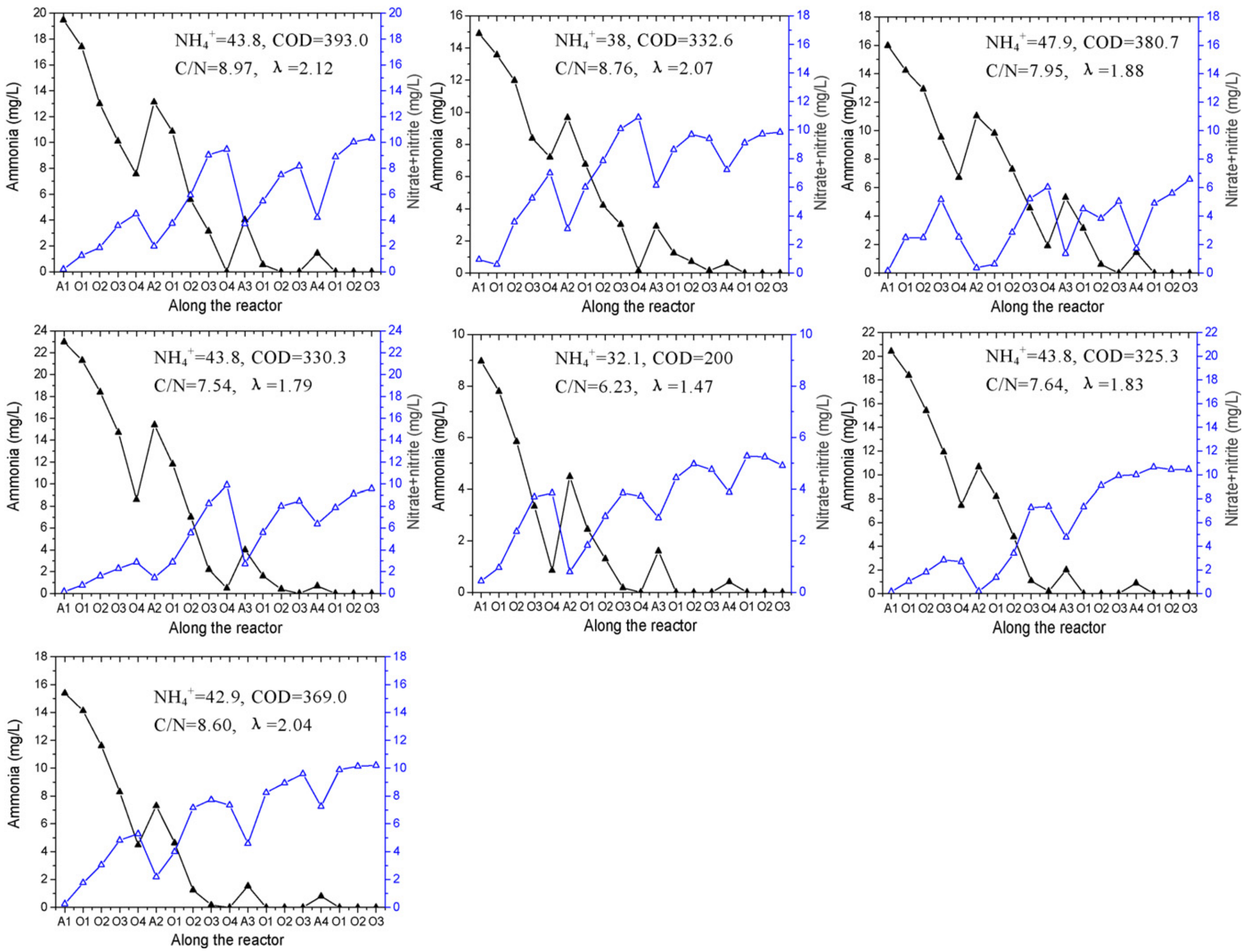

Fig. 3. Variations of ammonia and NO_X–N concentrations before calibration under different C/N ratios. In the X-axis the letter A means anoxic zone, O means aerobic zone and the Arabic numerals mean the compartment number. (▲) Ammonia; (□) nitrate + nitrite. The value of λ was calculated from model.

3.2. Development of fuzzy control model of step feeding process

3.2.1. Input and output variables and control rules

Based on bench-scale research the influent C/N ratio was selected as the input variable of fuzzy model, and the output variables were as follows: inflow rate distribution ratio (λ), volume of first stage (V_1), volume of second stage (V_2), volume of third stage (V_3), volume of fourth stage (V_4), volume of anoxic zone in first stage (V_{1A}), volume of anoxic zone in second stage (V_{2A}), volume of anoxic zone in third stage (V_{3A}), volume of anoxic zone in fourth stage (V_{4A}). The statuses of each variable were expressed as “Low”, “Moderate Low”, “Moderate”, “Moderate High” and “High”. The classical Mamdani method was used to fuzzify and defuzzify the input and output variables. Based on the bench-scale experimental results several fuzzy control rules were established using classical IF THEN manner, as shown in Table 2.

3.2.2. Input and output curve and membership function

In this research the Fuzzy Logic Toolbox of MATLAB 6.5 was used to establish the membership functions. In this process along with the Mamdani method some man-made experience are taken into accounted as references. For example the C/N ratio of 6.09 is looks as the lower value. The C/N ratio of 13 is reversely as the higher value. This is the key process to establish the membership function. As soon as this important procedure is well done, the input and output curve of the fuzzy model are built automatically by the software of Toolbox of MATLAB 6.5, as shown in Fig. 2.

3.3. Calibration of the fuzzy control model with domestic wastewater in pilot-scale experiments

3.3.1. Calibration of the fuzzy control model under various influent C/N ratios

After the establishment of the fuzzy control model the more important work is to calibrate and study the applicability of this fuzzy model. The calibration of the fuzzy model was investigated in Beijing University of Technology with wastewater of inhabitation district. Equipped with the fuzzy model pilot-scale experiments were carried out for exploring the system potential on removing nitrogen under different C/N ratios. The experimental procedures and results are shown in Fig. 3.

According to Fig. 3, in all the seven group experiments, ammonia can be removed completely, and no ammonia was detected in the effluents. Because of that, the variation of COD along the process was not depicted in figure [10]. The activated sludge presented a good sedimentation property with a stable SVI varying among 87–113 mL/g. However, the low efficiency on removing total nitrogen can be deduced from the results, which partially owing to the accumulation of nitrate in the anoxic zone of the system. While the C/N ratio of the influent was fixed, the higher inflow rate distribu-

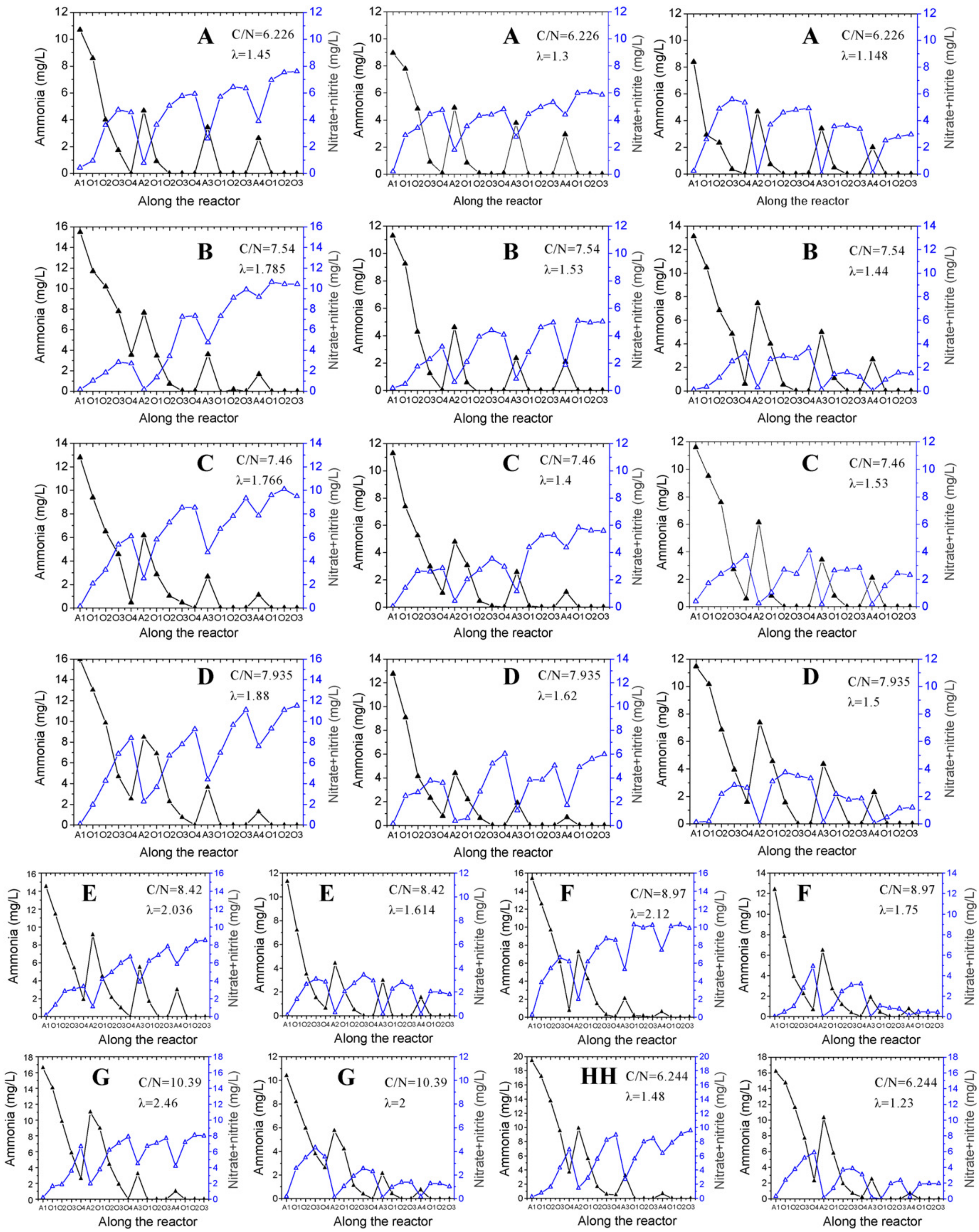

Fig. 4. Experimental results of pilot-scale experiments before and after calibration. In the *X*-axis the letter A means anoxic zone, O means aerobic zone and the Arabic numerals mean the compartment number. (▲) Ammonia; (□) nitrate + nitrite. (A) COD = 200, NH_4^+ = 32.12; (B) COD = 330.3, NH_4^+ = 43.80; (C) COD = 342, NH_4^+ = 45.8; (D) COD = 380.7, NH_4^+ = 47.9; (E) COD = 310, NH_4^+ = 50.5; (F) COD = 369, NH_4^+ = 42.9; (G) COD = 393.3, NH_4^+ = 43.80; (H) COD = 440, NH_4^+ = 42.3. Unit: mg/L.

tion ratio was, the more COD would enter into the forepart, which resulted in the concentration of nitrate in the anoxic zone increasing and cumulating to the next stage. Ingravescently, the accumulation of nitrate would finally result in the high concentration of total nitrogen in the effluent. The figure also showed that the accumulation of nitrate could be observed in the anoxic zone of all the stages of all the seven group experiments except the first stage. Generally, when the accumulation started in the second stage, the concentration of the nitrate tended to increase in the following two stages, all of these resulted in poor performance on removing total nitrogen. Based on above discussion, the direct inducement of effluent deterioration was the high inflow rate distribution ratio. The difference of inflow rate distribution ratios of original control model output and measured value was attributed to experimental wastewater component. So the pilot-scale experiment was necessary to calibrate the model with domestic sewage as the influent.

The calibration studies of the fuzzy control model were performed with real sewage of habitation district of Beijing University of Technology. During the experimental period the step feeding process was initially operated with the theoretical model output value (inflow rate distribution ratio). Afterwards the values of inflow rate distribution ratios were adjusted gradually. Based on the optimization rules the process was operated with no nitrate accumulation in each anoxic zone and minimal inflow rate in last stage. Under each condition the process has been operated over two times sludge age period. At last the maximal inflow rate distribution ratios were achieved under various influent C/N ratios. The experimental results are shown in Fig. 4.

From the figure the optimization operation and performance of step feeding process were implemented. With the calibrated inflow rate distribution ratio there was no nitrate or nitrite accumulation in each anoxic zone. The effluent ammonia concentrations were all below the detected level. The concentrations of effluent total nitrogen were only produced by the ammonia nitrogen in the aerobic zone of the last stage.

3.3.2. Adjustment of fuzzy model

Comparison of the maximal inflow rate distribution ratios coming from both original fuzzy model and calibrated one under the same influent C/N ratio was studied. The results were shown in Fig. 5. There was a strong linear relationship between these two maximal inflow rate distribution ratios as follows:

$$Y = 0.82776X \quad (1)$$

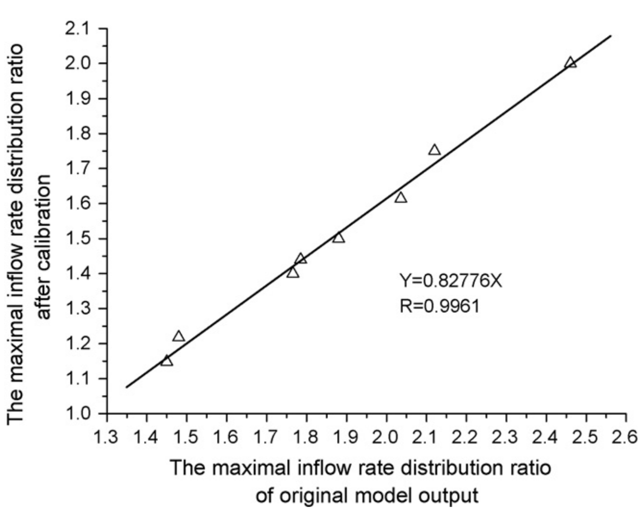

Fig. 5. Relationship of the maximal inflow rate distribution ratio of original model output value and calibrated one under the same influent C/N ratios.

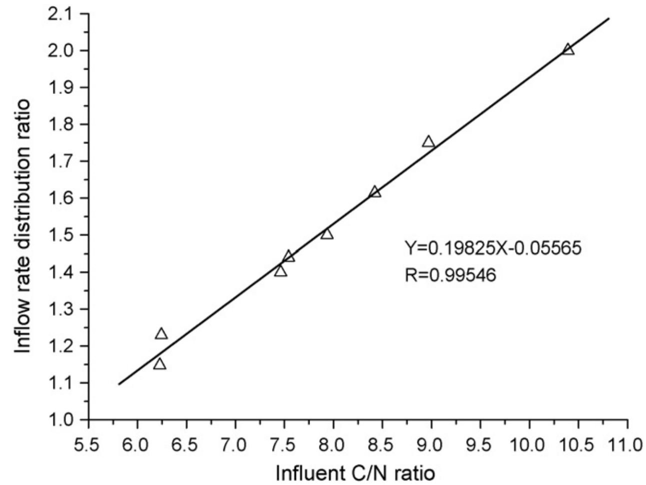

Fig. 6. Relationship of influent C/N ratio and maximal inflow rate distribution ratio in pilot-scale experiments.

in which the X stands for model output value, and Y stands for the real and measured value of pilot-scale experiments. Based on this equation the calibrated model output value could be applied in real treatment system.

According to the pilot-scale experimental results the linear relationship of influent C/N ratios and maximal inflow rate distribution ratios was obtained in Fig. 6 and as follows:

$$Y = 0.19825X - 0.05565 \quad (2)$$

in which X stands for influent C/N ratio and Y stands for the maximal inflow rate distribution ratio of pilot-scale experiments.

This equation provided a new and easy approach to calibrate the model. With a fixed influent C/N ratio the step feeding process could be operated under a certain inflow rate distribution ratio obtained with Eq. (2).

3.4. Application of fuzzy model for improving nitrogen removal

Based on calibrated fuzzy model pilot-scale experiments with domestic sewage were conducted for three months (from 9-4-2007 to 12-7-2007). As above mentioned the concentration of total nitrogen in the effluent was determined by the Kjeldahl nitrogen in the aerobic zone of the last stage, only if in each stage, complete nitrification and denitrification in aerobic and anoxic zone were realized respectively. In the last stage, where there was no nitrate accumulation and the inflow was at the minimum ratio, total nitrogen concentration in the effluent could be maintained at the lowest level. During the experimental period the value of influent C/N ratio (input variable) would be measured firstly. Then the values of inflow rate distribution ratio and volume distribution (output variables) were obtained with the model. Afterwards the output variables were calibrated with Eqs. (1) and (2). In the experiments the nitrification reaction of each stage proceeded thoroughly without ammonia detected. There was also no nitrate accumulation in the anoxic zone. The effluent total nitrogen concentrations were all kept at a relative low level with the calibrated model although the influent total nitrogen concentration varied dynamically. It should be emphasized that high nitrogen removal efficiency, higher than 95.1%, could be obtained with influent C/N of 8.16–12.3. Effluent total nitrogen concentrations were always below 2.36 mg/L during experimental periods. The SVI values were in the range of 92–115 mL/g, average value of 98 mL/g.

4. Conclusion

To optimize operation and performance of step feeding process, it is important to develop computer operational decision support system and intelligent control system. Fuzzy control has become an important and effective tool to help build such intelligent system. In this paper a fuzzy control model of anoxic/oxic step feeding activated sludge process for improving nitrogen removal was developed. The fuzzy control model selected influent C/N ratio as the input variable, and selected inflow rate and volume distribution as the output variables. Moreover, the calibration methods of control model for application in real sewage treatment plant have also been verified and approved. At last pilot-scale studies of the step feeding anoxic/oxic activated sludge process operated with the calibrated fuzzy model for improving nitrogen removal was investigated. The experimental results showed that high nitrogen removal efficiency, higher than 95.1%, could be obtained in step feeding process with the fuzzy model under the condition of influent C/N of 8.16–12.3. Moreover, the number of input variable was only one, which enhancing the applicability of fuzzy model. In addition only five control rules also enhanced the readability of the fuzzy model. The practical operation of step feeding process approved the validity, credibility and applicability of the fuzzy model. However, the robustness of the fuzzy model was not studied because the influent C/N ratio did not vary remarkably.

Acknowledgements

This research is financially supported jointly by the project of scientific research base and scientific innovation platform of Beijing municipal education commission (PXM2008_014204_050843), National Natural Science Foundation of China (No.20877086) and Knowledge Innovation Program of the Chinese Academy of Sciences (RCEES-QN-200706) and the Special Funds for Young Scholars of RCEES, CAS.

References

[1] S. Fujii, Theoretical analysis on nitrogen removal of the step-feed anoxic-oxic activated sludge process and its application for the optimal operation, Water Science and Technology 34 (1996) 459–466.
[2] L. Larrea, A. Larrea, E. Ayesa, J. Rodrigo, M. Lopez-Carrasco, J. Cortacans, Development and verification of design and operation criteria for the step feed process with nitrogen removal, Water Science and Technology 43 (2001) 261–268.
[3] G. Zhu, Y. Peng, Theoretical evaluation on nitrogen removal of step-feed anoxic/oxic activated sludge process, Journal of Harbin Institute of Technology 16 (2006) 99–102.
[4] J. Fillos, V. Diyamandoglu, L. Carrio, L. Robinson, Full-scale evaluation of biological nitrogen removal in the step-feed activated sludge process, Water Environment Research 68 (1996) 132–142.
[5] S. Schlegel, Operational results of waste water treatment plants with biological N and P elimination, Water Science and Technology 25 (1992) 241–247.
[6] R. Kayser, G. Stobbe, M. Werner, Operational results of the Wolfsburg wastewater treatment plant, Water Science and Technology 25 (1992) 203–209.
[7] E. Gorgun, N. Artan, D. Orhon, S. Sozen, Evaluation of nitrogen removal by step feeding in large treatment plants, Water Science and Technology 34 (1996) 253–260.
[8] S. Wang, L. Yu, G. Man, H. Zhu, D. Peng, X. Wang, A pilot study on a step-feeding anoxic/oxic activated sludge system, Water Science and Technology 53 (2006) 95–101.
[9] G.B. Zhu, Y.Z. Peng, S.Y. Wang, S.Y. Wu, B. Ma, Effect of influent flow rate distribution on the performance of step-feed biological nitrogen removal process, Chemical Engineering Journal 131 (2007) 319–328.
[10] G.B. Zhu, Performance and optimization of anoxic/oxic step feeding enhanced biological nitrogen removal process, Harbin Institute of Technology, Harbin, 2006.
[11] C. Chang, Y. Ma, C. Lo, Application of oxidation–reduction potential as a controlling parameter in waste activated sludge hydrolysis, Chemical Engineering Journal 90 (2002) 273–281.
[12] R. Tong, M. Beck, A. Latten, Fuzzy control of the activated sludge waste-water treatment process, Automatica 16 (1980) 695–701.
[13] T. Kalker, C. Van Goor, P. Roeleveld, M. Ruland, R. Babuska, Fuzzy control of aeration in an activated sludge wastewater treatment plant: design, simulation and evaluation, Water Science and Technology 39 (1999) 71–78.
[14] M. Fiter, D. Guell, J. Comas, J. Colprim, M. Poch, I. Rodriguez-Roda, Energy saving in a wastewater treatment process: an application of fuzzy logic control, Environmental Technology 26 (2005) 1263–1270.
[15] J. Ferrer, M. Rodrigo, A. Seco, J. Penya-Roja, Energy saving in the aeration process by fuzzy logic control, Water Science and Technology 38 (1998) 209–217.
[16] Y. Tsai, C. Ouyang, M. Wu, W. Chiang, Effluent suspended solid control of activated sludge process by fuzzy control approach, Water Environment Research 68 (1996) 1045–1053.
[17] M. Yong, P. Yong-Zhen, W. Xiao-Lian, W. Shu-Ying, Intelligent control aeration and external carbon addition for improving nitrogen removal, Environmental Modelling and Software 21 (2006) 821–828.
[18] E. Murnleitner, T. Becker, A. Delgado, State detection and control of overloads in the anaerobic wastewater treatment using fuzzy logic, Water Research 36 (2002) 201–211.
[19] Y. Peng, J. Gao, S. Wang, M. Sui, Use of pH as fuzzy control parameter for nitrification under different alkalinity in SBR process, Water Science and Technology 47 (2003) 77–84.
[20] A. Traoré, S. Grieu, S. Puig, L. Corominas, F. Thiery, M. Polit, J. Colprim, Fuzzy control of dissolved oxygen in a sequencing batch reactor pilot plant, Chemical Engineering Journal 111 (2005) 13–19.
[21] G.B. Zhu, Y.Z. Peng, Application and development of intelligent control technology in urban wastewater treatment system, Journal of Harbin Institute of Technology 36 (2004) 328–332.
[22] G. Zhu, Y. Peng, L. Zhai, Y. Wang, S. Wang, Performance and optimization of anoxic/oxic step feeding enhanced biological nitrogen removal process, Biochemical Engineering Journal 43 (2009) 280–287.
[23] G.B. Zhu, Y.Z. Peng, S.Y. Wang, Hydraulic method of controlling solids retention time in step-feed biological nitrogen removal process, Environmental Engineering Science 24 (2007) 1112–1121.
[24] APHA, Standard Methods for the Examination of Water and Wastewater, American public health association/American water works association/ Water Environment Federation, Washington, DC, USA, 1995.