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Control strategy of shortcut nitrification

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Abstract: Shortcut nitrification for ammonium-rich wastewater is energy-saving and cost-effective procedure that has become one of the hotspots in the field of biological denitrogenation. An orthogonal experiment was performed to study the combined effects of operational parameters on the performance of internal-loop airlift bioreactor for shortcut nitrification. The optimum operational parameters for the shortcut nitrification were found as temperature 35℃, pH 8.0, dissolved oxygen concentration 1.0 mg/L, ammonium concentration 4 mmol/L and HRT 16 h, which have different influence on the performance of shortcut nitrification reactor. The pH, temperature and dissolved oxygen concentration have significant bearing on the process. The results showed that the shortcut nitrification reactor could be successfully started up within 42 d, and the reactor performance is steady with minimum NO_2^-/NO_x^- of 85.2%, maximum 93.4% and average value of 91.4% in effluent. Based on the analysis of experimental data, a new control strategy named "priority + combination" for shortcut nitrification was suggested. Through this strategy, the startup and operation of shortcut nitrification for ammonium-rich sludge digester liquids were optimized. The control strategy works well to keep the reactor operation in steady state and in achieving high-efficiency for shortcut nitrification.

Keywords: internal-loop airlift bioreactor; shortcut nitrification; orthogonal experiment; control strategy; sludge digester liquids

Introduction

Nitrification is an important process in biological denitrogenation of ammonium-rich wastewaters. Shortcut nitrification means ammonium oxidation, which is the first step during nitrification. As compared with normal nitrification, shortcut nitrification can save energy, reduce cost, improve bioreactor efficiency and reduce sludge output (Verstraete and Philips, 1998). Therefore, many studies on shortcut nitrification have been carried out. Some new processes of biological nitrogen removal based on shortcut nitrification have been exploited, such as shortcut nitrification-denitrification and shortcut nitrification-anaerobic ammonium oxidation (Anammox)(van Kempen *et al.*, 2001; Zhang *et al.*, 2004; Zheng *et al.*, 2004). Among them, shortcut nitrification is the rate-limiting step and has become one of the hotspots in the field of biological nitrogen removal from wastewater. The performance of shortcut nitrification is correlated to operational parameters such as temperature, pH and dissolved oxygen etc. These operational parameters have been studied extensively and their suitable ranges were suggested by some researchers (Antoniou *et al.*, 1990; Laanbroek *et al.*, 1994; Daniel *et al.*, 1998; Hellinga *et al.*, 1998). However, the effects of these operational parameters on shortcut nitrification are quite different, and the combined effects are not equivalent to the simple superimposition of the effect of individual parameter. Therefore it is necessary to study the orderly array and the combined effects of operational parameters upon the process. Based on present investigation, a new control strategy was suggested which is quite important to achieve high-efficiency shortcut nitrification.

1 Materials and methods

1.1 Experimental apparatus

The laboratory-scale internal-loop airlift bioreactor is shown in Fig.1. It is made of polymethyl methacrylate with a total volume of 10.4 L and height of 36 cm, and it consists of four sections: riser, downcomer, separating section for gas and liquid, and settler. The cross sectional area of riser, downcomer and settler is 153.9 cm^2, 97.4 cm^2 and 346.4 cm^2, respectively. The influent is pumped into the bottom of the reactor. The liquid is aerated by a gas pump. Because of the buoyancy, the air bubbles move

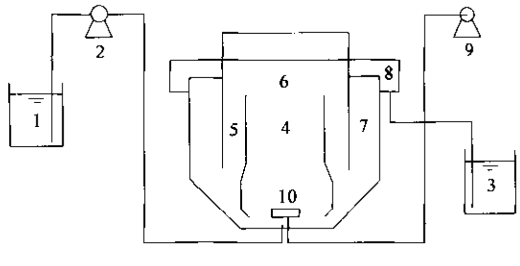

Fig.1 The device sketch of internal-loop airlift bioreactor
1. Influent bottle; 2. influent pump; 3. effluent bottle; 4. riser; 5. downcomer; 6. separating section for gas and liquid; 7. settler; 8. overflow weir; 9. aeration pump; 10. blowhole

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upward and most of them escape from top of the riser, leading to the different volumes of air retention in the riser and downcomer, which creates a density difference that causes the fluid to move from bottom of the downcomer to the riser, thus the internal-loop of liquid comes into being.

1.2 Inoculum

Aerobic activated sludge from Sibao Sewage Plant in Hangzhou, China was used as inoculum for the present study. Some physical and chemical characteristics of inoculum are as follows: pH 7.02, volatile suspended solids (VSS) 8.7 g/L, total suspended solids(TSS) 16.9 g/L, and VSS/TSS 51.6%.

1.3 Basal medium

1.3.1 Synthetic ammonium-containing wastewater

While studying the effects of operational parameters on shortcut nitrification, synthetic ammoniumcontaining wastewater was used as basal medium to control experimental conditions more stably, which would be helpful for enhancing the reliability of experimental data. The composition of wastewater is listed in Table 1.

Table 1 Composition of synthetic ammonium-containing wastewater

Component	Concentration, g/L	Component	Concentration, g/L
NaCl	0.585	$CaCl_2 \cdot 2H_2O$	0.147
KCl	0.074	KH_2PO_4	0.054
$MgSO_4 \cdot 7H_2O$	0.049	$(NH_4)_2SO_4$	Added as need
$NaHCO_3$	Added as needed	Trace elements solution*	1 ml/L

Note: Trace elements solution (g/L): $FeSO_4 \cdot 7H_2O$ 0.973; H_3BO_4 0.049; $ZnSO_4 \cdot 7H_2O$ 0.043; $MnSO_4 \cdot H_2O$ 0.034; $(NH_4)_6 \cdot Mo_7O_{24} \cdot 4H_2O$ 0.037; $CuSO_4 \cdot 5H_2O$ 0.025; HCl 0.00073

1.3.2 Sludge digester liquids

Sludge digester liquids with high ammonium concentration from Sibao Sewage Plant, Hangzhou were used as basal medium to verify the control strategy for shortcut nitrification. The quality of the wastewater is: ammonium concentration 30 mmol/L, COD 200 mg/L and pH 7.6.

1.4 Analytical methods

Ammonium, nitrite and nitrate were measured using the standard methods for examination of water and wastewater(APHA, 1995). The pH was measured by pHS-9V pH-meter, DO by JPB-607 dissolved oxygen meter, air flux by BSD-2 gas-meter and temperature by mercury thermometer.

1.5 Design of experiment scheme

The main operational parameters that influence the shortcut nitrification include temperature, pH, dissolved oxygen concentration, ammonium concentration and HRT. While studying factors one by one, comprehensive experiments should be carried out, which are too complicated to be put into practical use and to reflect the combined effects of operational parameters. Based on mathematical optimization theory, the orthogonal experiment was chosen to study the combined effects of operational parameters on performance of shortcut nitrification. In orthogonal experiment, the levels of factors (operational parameters above) were selected in the usual range during the operation of shortcut nitrification, which are listed in Table 2.

Table 2 Factor and its level in orthogonal experiment

Level	A	B	C	D	E
1	26	7.2	0.6	2	8
2	29	7.6	1.0	4	12
3	32	8.0	1.4	6	16
4	35	8.4	1.8	8	20

Notes: A. temperature,℃; B. pH; C. dissolved oxygen concentration, mg/L; D. ammonium concentration, mmol/L; E. HRT, h

NO_2^-/NO_x^- was used as index of shortcut nitrification and the higher is the ratio, the better is the performance of shortcut nitrification. The reactor must be kept steady for 3—5 d before each measure of NO_2^-/NO_x^- to ensure dependability of the data. Every time, the samples were taken in triplicate and the interval of 6 h was chosen. If the relative errors of the three measured values were less than 5%, the reactor performance was considered to be in steady state, and their average value was used as the ultimate value of NO_2^-/NO_x^-.

2 Results and discussion

2.1 Results

According to the orthogonal experiment $[L_{16}(4^5)]$ design, the shortcut nitrification reactor was run and its results are shown in Table 3.

It can be seen from Table 3 that there is obvious variance among the ultimate value of NO_2^-/NO_x^- in every experiment, which indicates that different combinations of these factors exert different effects on shortcut nitrification.

2.2 Analysis

2.2.1 Range analysis

Range analysis of orthogonal experiment was carried out and the results are listed in Table 4.

As shown in Table 4, $\bar{k}_{ij}=k_{ij}/n$ $(i = 1, 2, 3, 4;\ j = 1, 2, 3, 4, 5)$. Where, k_{ij} is the sum of measured values corresponding to level i of factor j, n is the occurrence

Table 3 Results of orthogonal experiment [$L_{16}(4^5)$]

Experiment No.	A	B	C	D	E	NO_2^-/NO_x^-
1	1	1	1	1	1	0.602
2	1	2	2	2	2	0.856
3	1	3	3	3	3	0.868
4	1	4	4	4	4	0.699
5	2	1	2	3	4	0.802
6	2	2	1	4	3	0.885
7	2	3	4	1	2	0.798
8	2	4	3	2	1	0.856
9	3	1	3	4	2	0.839
10	3	2	4	3	1	0.833
11	3	3	1	2	4	0.929
12	3	4	2	1	3	0.865
13	4	1	4	2	3	0.799
14	4	2	3	1	4	0.878
15	4	3	2	4	1	0.926
16	4	4	1	3	2	0.866

Notes: A. temperature,℃ ; B. pH; C. dissolved oxygen concentration, mg/L; D. ammonium concentration, mmol/L; E. HRT, h

Table 4 Range analysis of orthogonal experiment

Item	A	B	C	D	E
$\bar{k}_{1j}$	0.752	0.756	0.817	0.781	0.800
$\bar{k}_{2j}$	0.836	0.863	0.862	0.860	0.840
$\bar{k}_{3j}$	0.866	0.880	0.860	0.842	0.854
$\bar{k}_{4j}$	0.868	0.821	0.782	0.838	0.827
R_j	0.116	0.124	0.080	0.079	0.054

Notes: A. temperature,℃ ; B. pH; C. dissolved oxygen concentration, mg/L; D. ammonium concentration, mmol/L; E. HRT, h

number of level i of factor j. The optimal level of one factor could be determined by k_{ij}, the level corresponding to max ($\bar{k}_{1j}$, $\bar{k}_{2j}$, $\bar{k}_{3j}$, $\bar{k}_{4j}$) is optimal. R_j is range of factor, R_j= max($\bar{k}_{1j}$, $\bar{k}_{2j}$, $\bar{k}_{3j}$, $\bar{k}_{4j}$) - min ($\bar{k}_{1j}$, k_{2j}, $\bar{k}_{3j}$, $\bar{k}_{4j}$). R_j could determine the influence degree of factor on performance of shortcut nitrification. The higher is R_j of one factor, the bigger is its influence degree.

According to the results of range analysis(Table 4), $A_4B_3C_2D_2E_3$ is judged as the combination of optimal level of all factors by max($\bar{k}_{1j}$, $\bar{k}_{2j}$, k_{3j}, $\bar{k}_{4j}$), that is, temperature 35℃, pH 8.0, dissolved oxygen concentration 1.0 mg/L, ammonium concentration 4 mmol/L and HRT 16 h. And R_j shows that these factors have different influence on performance of shortcut nitrification with an order of pH (B), temperature (A), dissolved oxygen concentration (C), ammonium concentration(D), HRT(E).

2.2.2 Analysis of variance

Analysis of variance for orthogonal experiment was carried out, which is helpful to distinguish the variations of NO_2^-/NO_x^- caused by different levels of factors and experimental error, and can be used to determine the influence level of concerned factor. The results are shown in Table 5.

Table 5 Variance analysis of orthogonal experiment

Source of variation	Sum of square	Degree of freedom	Mean square	F	$F_{0.10}$	Significance
A	0.036	3.000	0.012	6.000	5.390	**
B	0.037	3.000	0.012	6.167	5.390	**
C	0.033	3.000	0.011	5.402	5.390	*
D	0.014	3.000	0.005	2.333	5.390	
E	0.006	3.000	0.002	1.000	5.390	
Error	0.006	3.000	0.002			

Notes: ** Very significant; * significant

According to F-statistics, these factors have different influence on performance of shortcut nitrification with an order of B, A, C, D, E, which is similar to the results of range analysis. Comparing F-statistics with the critical F-value at 10% level, pH, temperature and dissolved oxygen concentration were found to be significant($p<0.10$).

2.3 Control strategy for shortcut nitrification

According to the analysis of experimental results, a new control strategy named "priority+combination" for shortcut nitrification was suggested.

2.3.1 Priority control strategy

Because the factors under investigation have different influence on the performance of shortcut nitrification, it is necessary to discriminate them for optimizing shortcut nitrification. The significant factors should be given priority and the others should be ignored, which is priority control.

2.3.2 Combination control strategy

As shown in Table 3, the value of NO_2^-/NO_x^- is not always high even when a certain significant factor is in its optimal level. It might be due to that single significant factor is incapable to dominate shortcut nitrification. So, it is necessary to consider the combined effects of operational parameters on performance of shortcut nitrification, which is combination control.

Based on the "priority + combination" control strategy, the significant factors (pH, temperature and dissolved oxygen concentration) were selected and controlled together in practice. The detailed scheme is listed below: (1) The pH was controlled around 8.0, and was prevented from fluctuation. (2) According to the results of range analysis (Table 4), $\bar{k}_{ij}$ of temperature 32℃ and 35℃ are quite approximate, so temperature could be controlled between 32℃ and

35℃. (3) According to the results of range analysis (Table 4), k_{ij} of dissolved oxygen concentration of 1.0 mg/L and 1.4 mg/L are quite approximate too. Considering energy-saving, dissolved oxygen concentration could be controlled around the lower limit of 1.0—1.4 mg/L, while taking an account of reaction rate, it could be controlled around the upper limit of 1.0—1.4 mg/L. (4) Ammonium concentration and HRT were controlled in the usual range. (5) In addition, sludge retention time(SRT) was fixed at 14 d to wash out the nitrite oxidizer that oxidizes nitrite to nitrate and thus makes shortcut nitrification unstable.

By means of this new control strategy, the quick startup and operation of shortcut nitrification for ammonium-rich sludge digester liquids were optimized, and the results are shown in Figs.2 and 3.

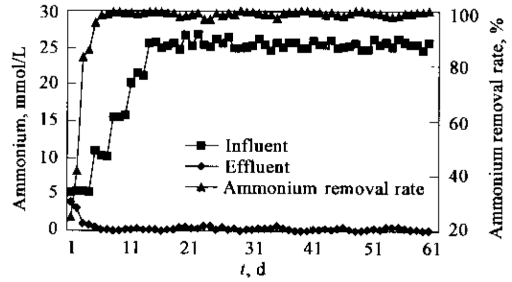

Fig.2 Variation of ammonium in influent and effluent, and ammonium removal during startup and steady state of shortcut nitrification

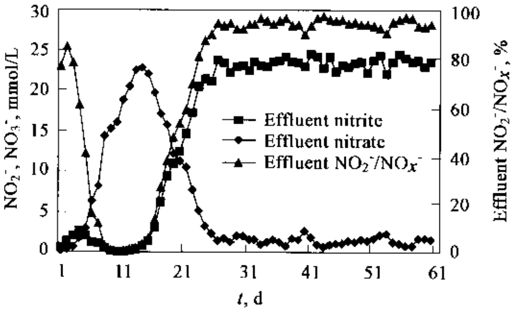

Fig.3 Variation of nitrite, nitrate and percentage of nitrite account for NO_x^- in effluent during startup and steady state of shortcut nitrification

The results showed that the shortcut nitrification reactor could be successfully started up within 42 d and the reactor performance is good and steady with minimum NO_2^-/NO_x^- of 85.2%, maximum 93.4% and average value of 91.4% in effluent, these index values are obviously better than those of shortcut nitrification reported in literature(Garrido *et al.*, 1997; Ruiz *et al.*, 2003). The control strategy works well to keep the reactor in steady operation and achieve high-efficiency of shortcut nitrification, so it can be applied to guide the operation of shortcut nitrification reactor effectively.

3 Conclusions

Based on the operation of internal-loop airlift bioreactor for shortcut nitrification, the orthogonal experiment was carried out to study the combined effects of operational parameters on performance of shortcut nitrification. Following conclusions can be drawn from the results:

(1) The optimum operational parameters are temperature 35℃, pH 8.0, dissolved oxygen concentration 1.0 mg/L, ammonium concentration 4 mmol/L and HRT 16 h. The order of the influence of operational parameters on shortcut nitrification is pH, temperature, dissolved oxygen concentration, ammonium concentration, HRT. Among them, pH, temperature and dissolved oxygen concentration are significant factors.

(2) A new control strategy named "priority + combination" for shortcut nitrification was suggested. By means of this new control strategy, the significant factors were controlled together to optimize the quick startup and operation of shortcut nitrification for sludge digester liquids with high ammonium concentration. The control strategy works well and can be applied to guide the operation of shortcut nitrification reactor.

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