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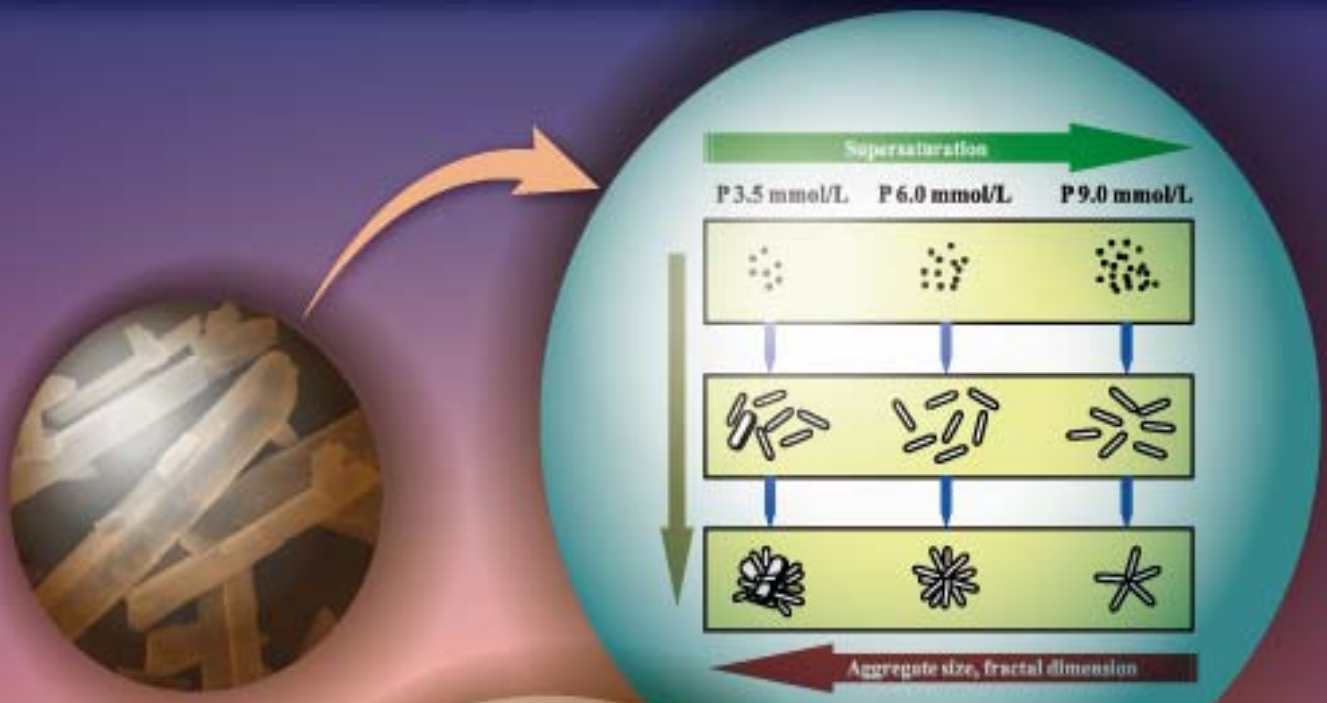

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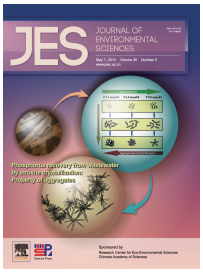

Effect of alkalinity on nitrite accumulation in treatment of coal chemical industry wastewater using moving bed biofilm reactor

Baolin Hou, Hongjun Han*, Shengyong Jia, Haifeng Zhuang, Qian Zhao, Peng Xu

State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China, E-mail: hbl527@163.com

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ABSTRACT

Nitrogen removal via nitrite (the nitrite pathway) is more suitable for carbon-limited industrial wastewater. Partial nitrification to nitrite is the primary step to achieve nitrogen removal via nitrite. The effect of alkalinity on nitrite accumulation in a continuous process was investigated by progressively increasing the alkalinity dosage ratio (amount of alkalinity to ammonia ratio, mol/mol). There is a close relationship among alkalinity, pH and the state of matter present in aqueous solution. When alkalinity was insufficient (compared to the theoretical alkalinity amount), ammonia removal efficiency increased first and then decreased at each alkalinity dosage ratio, with an abrupt removal efficiency peak. Generally, ammonia removal efficiency rose with increasing alkalinity dosage ratio. Ammonia removal efficiency reached to 88% from 23% when alkalinity addition was sufficient. Nitrite accumulation could be achieved by inhibiting nitrite oxidizing bacteria (NOB) by free ammonia (FA) in the early period and free nitrous acid in the later period of nitrification when alkalinity was not adequate. Only FA worked to inhibit the activity of NOB when alkalinity addition was sufficient.

Introduction

With human progress and the improvement of living standards, an increasing amount of contaminants containing nitrogen have been discharged into the environment. The large amount of nitrogen discharged into water bodies has undermined the nitrogen cycle in nature, causing world-wide eutrophication that occurs repeatedly. Nitrogen removal has been a hot and difficult research issue in the environmental protection area. Numerous new theories and technology have been developed on the basis of traditional treatment theories and processes. Several typical new theories and processes have emerged such as: nitrogen removal via nitrite pathway (Hellinga et al., 1998; Van Hulle et al., 2007), anaerobic ammonium oxidation (Mulder et al., 1995; Strous et al., 1998), the combination of partial nitrification to nitrite and anaerobic ammonium oxidation (CANON) (Strous et al., 1999; Third et al., 2001) and the enhanced biological nitrification bacteria process (Salem et al., 2002), drawing a considerable amount of attention of scholars. New nitrogen removal theories and processes have shown great advantages compared to traditional theories and technology, especially nitrogen removal via the nitrite pathway and CANON, which are both based on partial nitrification to nitrite. The nitrite pathway is a more practical process among these new processes. Theoretically, nitrogen removal via nitrite yields a 25% reduction in oxygen demand and 40% reduction in carbon source requirement for denitrification.

Coal chemical industry wastewater is discharged in the processes of coal gasification and coal chemical production (Yang et al., 2006; Wang et al., 2010), the composition of which is very complex, containing various toxic compounds and a large number of refractory organic and inorganic contaminants, with poor biodegradability (Marañón et al., 2008). The wastewater characteristics vary significantly according to the coal quality used in the production. More than 244 kinds of organic com-

* Corresponding author. E-mail: han13946003379@163.com

pounds have been detected in the wastewater. Phenolic compounds are the main pollutants. The wastewater also contains polycyclic aromatic hydrocarbons, heterocyclic compounds, long-chain hydrocarbons, ammonia, cyanide and thiocyanate (Nakhla et al., 1990; Gai et al., 2008; Felföldi et al., 2010; Yu et al., 2010). Although the wastewater is pretreated via ammonia-stripping, it also contains a high concentration of ammonia. Nitrogen removal was unsatisfactory in the suspended activated sludge process due to the presence of toxic and inhibitory matter and limited available carbon sources (Kumar et al., 2000). Under high concentrations of phenolic compounds and inhibitors, nitrifying bacteria were out-competed in the suspended activated sludge system by the fast growth of heterotrophic microorganisms (Kim et al., 2007). However, the moving bed biofilm reactor has proved to be an effective process to remove both organic contaminants and ammonia in the treatment of coal chemical industry wastewater (Li et al., 2011). Considering the limited carbon source characteristic and complex composition of coal chemical industry wastewater, nitrogen removal via a nitrite pathway that requires less carbon source is a desirable method for the treatment of coal chemical industry wastewater. Alkalinity plays a vital role in nitrification, especially carbonate alkalinity. Alkalinity is not only the inorganic carbon source of heterotrophic nitrifying bacteria, but also balances the acid-base level of the mixture, affecting the state of matter present in aqueous solution. In this context, a moving bed biofilm reactor (MBBR) was adopted to treat coal chemical industry wastewater to investigate the effects of variations of nitrogen and alkalinity on the treatment process. The study involved five operation phases with different alkalinity dosage ratios. The effect of alkalinity on nitrification to nitrite and nitrite accumulation were the key issues to be investigated. The evolution of NH_4^+-N removal and nitrite accumulation were studied by raising the alkalinity dosage ratio stepwise.

1 Materials and methods

1.1 Experimental apparatus

The MBBR was a cylindrical Plexiglas reactor with an internal diameter of 120 mm and height of 450 mm. The effective volume of the MBBR was 4.85 L, followed by a 0.5 L settling tank. The suspended carriers used in the MBBR were circular polyethylene flakes, with a diameter of 22 mm and thickness of 1.5 mm. The density of the carriers was about 0.86 g/cm^3, lower than that of water. The density of carriers with attached wet biofilm was 1.11 g/cm^3. The filling ratio (volumetric filling in empty reactor) was 35%.

1.2 Inoculum and wastewater characteristics

Seed was collected from a full-scale coal chemical industry wastewater treatment plant in Harbin, China. The sludge was gray-black and the settling characteristic was good with a sludge volume index of 83.

Real coal chemical industry wastewater used in this study was obtained from the full-scale wastewater treatment facility of a coal chemical plant in Harbin, China. The characteristics of the wastewater as following: COD 895–1109 mg/L with mean value 1065 mg/L, total phenol 198–249 with mean 226 mg/L, NH_4^+-N 92–118 mg/L with mean 108 mg/L, and pH 6.5–7.5 with mean 7.16. Considering the fluctuations in the parameters of the real wastewater, the main parameters in the influent were controlled by adding tap water into the real wastewater. The concentration of ammonia was adjusted by adding ammonia chloride. Sodium bicarbonate was added to control alkalinity.

1.3 Experiment operation

Initially, the reactor ran for 30 days as a batch system after being inoculated with the seed sludge obtained from the full-scale facility, followed by a continuous flow process. A stable biofilm was formed on the carriers, with the biomass of 0.28 g VSS/g. During batch culture, the reactor was fed with the real wastewater diluted by adding tap water, with the COD concentration increasing stepwise from 500 to 1000 mg/L in three steps. The hydraulic retention time was 36 hr in the continuous flow process during the experimental period. The motion of carriers was driven by aeration introduced at the bottom of the reactor and the dissolved oxygen (DO) concentration was kept around 1.8 mg/L. The experiment operation was divided into 5 phases (**Table 1**) and the temperature was controlled at (25 ± 2)°C throughout the experiment.

Table 1 Operational conditions

Phase	Time (days)	COD (mg/L)	Total phenols (mg/L)	$NaHCO_3$ (dosage ratio)*
I	1–15	1002.65 ± 11.72	208.99 ± 5.24	–
II	16–30	501.95 ± 7.37	114.26 ± 5.38	–
III	31–45	504.28 ± 9.44	115.50 ± 5.66	2:1
IV	45–60	1000.46 ± 9.51	210.66 ± 6.89	2:1
V	61–75	998.78 ± 8.45	209.72 ± 5.83	0.5:1
	76–90			1:1
	91–105			1.5:1
	106–120			2:1
	121–135			2.5:1

*Dosage ratio: defined as the molar ratio of sodium bicarbonate to ammonia

1.4 Specific oxygen uptake rate test

Specific oxygen uptake rate (SOUR) is an important parameter to assess the activity of activated sludge. **Table 2** lists the substrate solutions for SOUR measurement. The SOUR test was conducted to investigate the distribution characteristics of the two kinds of nitrifying microorganism, ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB). Activated sludge from different samples was first separately maintained at 20°C and was continuously aerated to saturate it with a sufficient DO concentration. Then the activated sludge was centrifuged at the speed of 1400 r/min for 3 min. The centrifuged sludge samples were rinsed to wash out the NH_4^+, NO_2^- and NO_3^- adsorbed on the sludge. The substrate solutions (**Table 2**) were aerated for 2 hr to saturate the DO concentration at 20°C. The pretreated sludge and substrate solution were mixed into a 300 mL dissolved oxygen bottle, and the initial mixed liquor volatile suspended solids (MLVSS) was kept at 200 ± 20 mg VSS/L. Then each bottle was sealed carefully with a rubber stopper equipped with an IntelliCAL LDO probe (101, HACH, USA), without air bubbles inside. The mixtures were then incubated at 20°C and stirred with a magnetic stirrer. The DO concentration in each bottle was continuously monitored. The SOUR of each sample equaled the linear regression slope of the DO drop vs. time divided by the VSS concentration in the bottle. All batch tests were preformed in triplicate.

The substrate solution for SOUR measurement of AOB was without an organic carbon source or nitrite (**Table 2**). A 20-mmol $NaClO_3$ was added to the mixed solution as inhibitor to selectively prevent nitrite from being oxidized to nitrate (Belser and Mays, 1980; Hynes and Knowles, 1983). Allylthiourea (5 mg/L) was added into the feed solution for SOUR measurement of NOB as a selective inhibitor to keep ammonia from being oxidized to nitrite (Wood et al., 1981; Chung et al., 2006), because a small amount of ammonia might be left in the sludge or arise from endogenous nitrification. 100 mg/L COD was supplied by the coal chemical industry wastewater in terms of feed solution for SOUR measurement of heterotrophic microorganisms. Both selective inhibitors were added into the feed solution for SOUR measurement of heterotrophic microorganisms due to coal chemical industry wastewater including ammonia and nitrite. The endogenous respiration rate of the activated sludge was tested as blank. The substrate solution for blank measurement was without organic compounds, ammonia or nitrite, having minerals only. The net SOUR of each kind of microorganism was calculated by subtracting the SOUR caused by the endogenous respiration rate from the measured SOUR.

1.5 Analytical methods

COD, NH_4^+-N, NO_2^--N, NO_3^--N were measured daily in accordance with standard methods (APHA, 1998). Bicarbonate alkalinity was determined by a distillation method. pH and DO were measured using a pHC101 probe and IntelliCAL LDO probe, both of which were connected to a multifunction meter (HQ30d, HACH, USA).

2 Results and discussion

2.1 Relationships among alkalinity, pH and ion form

Generally, pH is in the range of 6.5–8.5 in common biological wastewater treatment systems, the alkalinity of which is composed of carbonate alkalinity (CO_3^{2-}, HCO_3^- and CO_2). There is also a buffer capacity in the carbonate balance system. The relationship between alkalinity and pH in the carbonate system is shown in **Fig. 1**.

The dissociation equilibrium in a carbonate solution

Table 2 Composition of the feed solutions for the SOUR tests

	Compound	Heterotrophic microorganism	AOB	NOB	Blank
Electron donor	Coal chemical industry wastewater (mg/L)	100	–	–	–
	NH_4Cl (mg/L)	–	100	–	–
	$NaNO_2$ (mg/L)	–	–	100	–
Buffer	KH_2PO_4 (mg/L)	0.85	0.85	0.85	0.85
	K_2HPO_4 (mg/L)	2.1	2.1	2.1	2.1
	$Na_2HPO_4·7H_2O$ (mg/L)	3.3	3.3	3.3	3.3
Inorganic salt	$MgSO_4·7H_2O$ (mg/L)	2.2	2.2	2.2	2.2
	$CaCl_2$ (mg/L)	2.7	2.7	2.7	2.7
	$FeCl_3·6H_2O$ (mg/L)	0.25	0.25	0.25	0.25
	KCl (mg/L)	3.2	3.2	3.2	3.2
	$MnSO_4·H_2O$ (mg/L)	1.6	1.6	1.6	1.6
	$NaHCO_3$ (mg/L)	800	800	800	800
Inhibitor	$NaClO_3$ (mmol)	20	20	–	–
	Allylthiourea (mg/L)	5	–	5	–

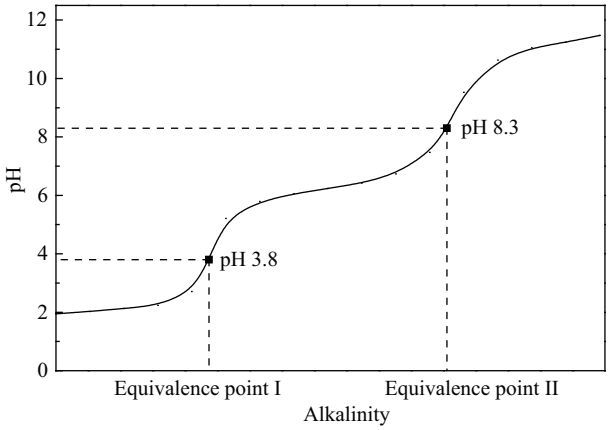

Fig. 1 Relationship between alkalinity and pH in carbonate system.

system can be described as following Reaction (1).

$$CO_2+H_2O\longleftrightarrow H_2CO_3\Longleftrightarrow H^++HCO_3^-\longleftrightarrow 2H^++CO_3^{2-} \quad (1)$$

CO_2 in water mainly exists in dissolved gas molecule form. Only a small part of CO_2 dissolved in water reacts with water to form carbonic acid. The sum of the two is referred as to free carbon dioxide. The first dissociation equilibrium constant can be calculated by Eq. (2):

$$K_1 = \frac{[H^+][HCO_3^-]}{H_2CO_3^-} = \frac{[H^+][HCO_3^-]}{[CO_2] + [H_2O]} \quad (2)$$

$K_1 = 4.45 \times 10^{-7}$ at 20°C.

The second dissociation equilibrium constant of HCO_3^- can be calculated by Eq. (3)

$$K_2 = \frac{[H^+][CO_3^{2-}]}{HCO_3^-} \qquad K_2 = 4.69 \times 10^{-11} \text{ at } 20°C. \quad (3)$$

The proportions of CO_2, HCO_3^- and CO_3^{2-} change with the variation of pH as shown in **Fig. 2**.

Ammonia is the energy and nitrogen source of nitrifying bacteria. Free ammonia (FA) is the real growth substrate of AOB, while a high concentration of FA shows an inhibitory effect on the activity of AOB and NOB. Forms of nitrogen in ammonia solution include NH_3 and NH_4^+, between which there is dissociation equilibrium (Reaction (4)).

$$NH_3 + H_2O\Longleftrightarrow NH_4^+ + OH^- \quad (4)$$

The proportion of FA can be estimated using Eq. (5).

$$\frac{C_{FA}}{C_{TNH_3}} = \frac{10^{pH}}{K_b/K_w + 10^{pH}} \quad (5)$$

where, K_b is the dissociation equilibrium constant ($K_b = 10^{-4.7}$ at 20°C). K_w is the ion product constant of water, ($K_w = 1 \times 10^{-14}$ at 20°C).

Free nitrous acid (FNA) is the feed of NOB; it can also inhibit the growth and activity of both AOB and NOB. The concentration of FNA (C_{FNA}) at different pH can be calculated by Eq. (6):

$$\frac{C_{FNA}}{C_{TNH_2}} = \frac{1}{1 + K_a \times 10^{pH}} \quad (6)$$

where, K_a is the dissociation equilibrium constant of nitrous acid ($K_a = 10^{-4.5}$ at 20°C). The proportion of FA and FNA as a function of pH can be calculated by Eqs. (5) and (6) (**Fig. 3**).

Alkalinity plays an important role in terms of both growth substrate and environment for microorganisms, especially in establishing a balanced system for the growth of AOB and NOB in the control of nitritation.

2.2 SOUR

The SOUR experiments were performed to assess the microbial distribution for sludge obtained from different periods. The proportions of the three kinds of microorganisms in activated sludge could be estimated according to the SOUR. **Figure 4** shows the decline of DO concentration per unit biomass and time of sludge collected from

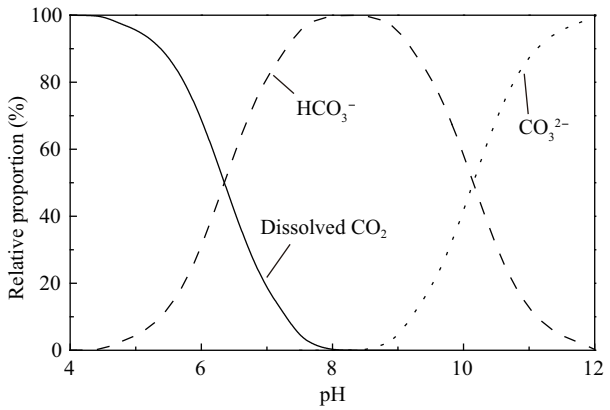

Fig. 2 Variation of form proportion with pH in carbonate system

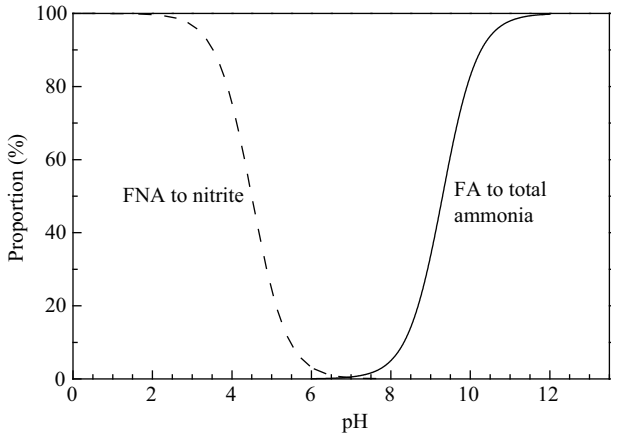

Fig. 3 Proportion of FA and FNA in the corresponding system.

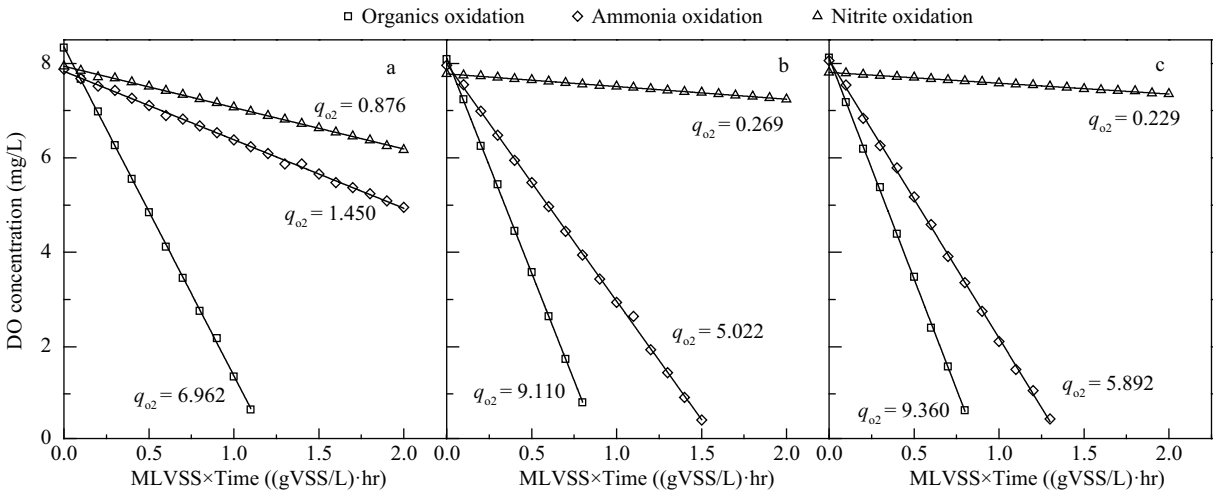

Fig. 4 SOUR tests for different sludge, (a) raw sludge, (b) suspended sludge in MBBR, (c) attached sludge in MBBR. q_{o2} is the value of SOUR.

different phases for three kinds of electron donors. After blank correction, the slope of each line represented the SOUR of the different microbial groups.

For organics (expressed as COD) oxidation, the SOURs of suspended and attached activated sludge in MBBR were 9.110 mg O_2/(g VSS·hr) and 9.360 mg O_2/(g VSS·hr), respectively, both higher than that of raw sludge (6.692 mg O_2/(g VSS·hr)), which demonstrated that the ability for organic contaminant (mainly phenolic compounds) degradation of activated sludge in the MBBR was promoted after domestication. The SOUR difference of suspended and attached activated sludge was not significant. The SOURs for the ammonia oxidation by suspended and attached sludge in the MBBR were 3.5 and 4 times higher than that of the original sludge respectively, suggesting that the biomasses of AOB in suspended and attached activated sludge were 3.5 and 4 times higher, assuming AOB in different sources with similar activity. For nitrite oxidation, the SOUR of raw sludge was estimated to be 3.5 times higher than that of the sludge in the MBBR. The distribution ratio of AOB to NOB was 1.65 assuming similar microbial activity, implying the presence of more AOB compared to NOB. In comparison, the ratios for suspended and attached activated sludge were calculated to be 18.67 and 25.73, indicating that AOB was dominant in the MBBR. The results indicated that there was a significant difference in microbial distribution for different activated sludge. In addition, AOB was more easily adapted for attached growth to the carrier. NOB was gradually eliminated by heterotrophic microorganisms and AOB via the synergetic inhibition of FA and FNA (Park et al., 2010a), when carbon source and DO were the limiting factors.

2.3 Ammonia removal efficiency

Treatment effectiveness during the first four phases is shown in **Fig. 5**. Removal of COD and total phenols stabilized after operation for about 7 days, and removal efficiency of COD and total phenols reached 81% and 90% respectively. However, ammonia removal efficiency was no more than 20%. COD and total phenol concentrations were reduced by half in the second phase by dilution with tap water. Removal of COD and total phenols were still stable and rose slightly, while ammonia removal was not enhanced yet. The SOUR test indicated that the sludge contained a certain amount of AOB. Ammonia removal efficiency was not promoted by diluting the contaminant concentrations, implying that toxic compounds in the coal chemical industry effluent were not the key factor inhibiting nitrification.

Sodium bicarbonate was added to supplement alkalinity from the third phase on, with the dosage ratio of 2:1. Ammonia removal efficiency ascended rapidly from 20% to 88% after adding sodium bicarbonate. Augmentation of the pollutant concentration in the influent induced a sudden rise of NH_4^+-N in the effluent (IV phase), while NH_4^+-N removal efficiency returned to the normal level (88%) in 4 days. The result suggested that alkalinity played a vital role in ammonia removal and was an important factor affecting AOB. The investigation also demonstrated that the toxicity of coal chemical industry wastewater was not the main inhibitory factor for nitrification.

The evolution of NH_4^+-N in the influent and effluent on heightening the alkalinity dosage ratio stepwise is illustrated in **Fig. 6**. NH_4^+-N removal efficiency dropped from 90% to 31% rapidly when the alkalinity dosage ratio varied between 2.0:1 and 0.5:1. NH_4^+-N removal efficiency ascended to 72% and then fell to 40% when the alkalinity dosage ratio rose to 1.0:1. The level of NH_4^+-N in the effluent at the dosage ratio of 1.5:1 was similar to that at the dosage of 1.0:1. When alkalinity was sufficient (dosage ratio $\geqslant$ 2.0:1), NH_4^+-N removal efficiency stabilized at around 89%.

NH_4^+-N removal increased first and then decreased, stabilizing at a low level when alkalinity addition was insufficient. Each 1.0 mol ammonia nitrification consumes 2.0 mol alkalinity theoretically, according to the nitri-

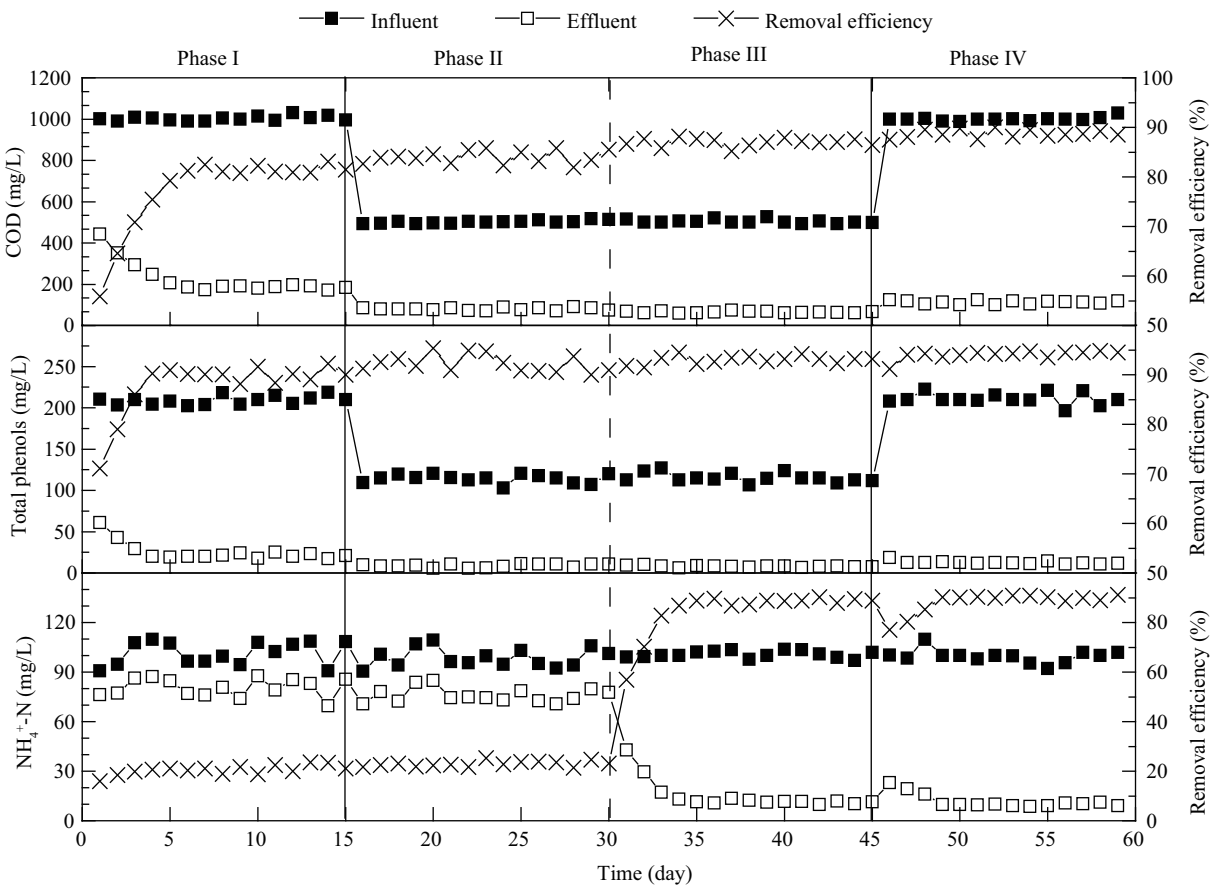

Fig. 5 Effect of alkalinity on treatment effectiveness.

fication chemical equation. Alkalinity consumption will attenuate the buffering capacity of the mixture, and result in a diminution of pH. On one hand, the fall of pH lowered the FA concentration, which was the real feed for AOB (Bagchi et al., 2010). According to the Monod equation, the reaction rate changes from a zero-order reaction to a pseudo first-order reaction when the substrate concentration decreases, especially when less than the saturation constant, causing the reduction of NH_4^+-N removal. On the other hand, the drop of pH attenuated the microbial activity of AOB, hindering nitrification. A peak was observed in terms of NH_4^+-N removal efficiency at each alkalinity dosage ratio when it increased from 0.5:1 to 1.5:1 stepwise. The peak removal efficiency exceeded the theoretical amount of NH_4^+-N removal (calculated by the ratio of alkalinity to sufficient alkalinity). It was difficult to give a definite reason for the peak, and this requires further study. NH_4^+-N removal was stable when alkalinity was adequate due to the successful nitrification, and this environmental condition was suitable for the growth and metabolism of nitrifying bacteria.

2.4 Nitrite accumulation

Nitrite accumulation is the primary step for biological nitrogen removal via nitrite. The evolution of nitrite accumulation throughout the experiment is illustrated in **Fig. 7**. The nitrite accumulation rate was very low when no extra alkalinity was added (phases I and II), and a small amount of nitrite accumulation was obtained at the end of phase II. 84% nitrite accumulation emerged with sufficient alkalinity addition (phases III and IV), which suggested that alkalinity was not only essential for ammonia removal, but also played a vital role in nitrite accumulation. The nitrite accumulation rate dropped to 37% in a short period of time when the alkalinity dosage ratio declined from 2:1 to 0.5:1. The nitrite accumulation rate continued to decrease and was stable at 30% when the alkalinity dosage ratio rose to 1.0:1. The nitrite accumulation rate rose to 84% and then dropped to 75% when the alkalinity dosage ratio increased to 1.5:1. The nitrite accumulation rate reached 96% when alkalinity addition was adequate (dosage ratio $\geqslant$ 2.0:1).

One of the essential requirements for nitrite accumulation is taking measures to suppress the activity of NOB but with no effect on AOB. According to the SOUR test, AOB was dominant compared to NOB in the reactor. However, the small amount of NOB would attenuate nitrite accumulation because nitrite oxidation to nitrate was much easier than ammonia oxidation to nitrite in the two-step nitrification. AOB are inhibited by FA in the range of 10–150 mg/L, while NOB are more sensitive to FA in the range of 0.1–1.0 mg/L (Anthonisen et al., 1976; Park and

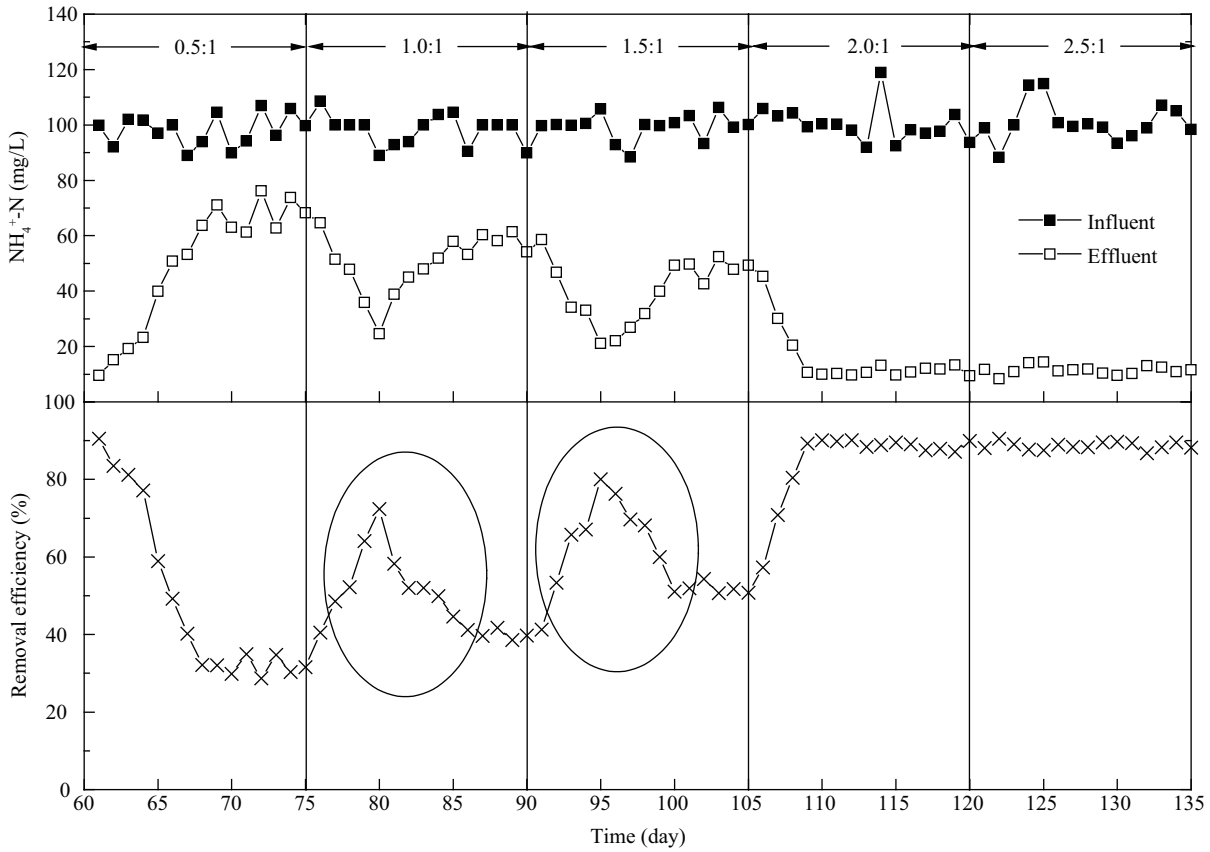

Fig. 6 Evolution of NH_4^+-N removal at different alkalinity dosage ratios.

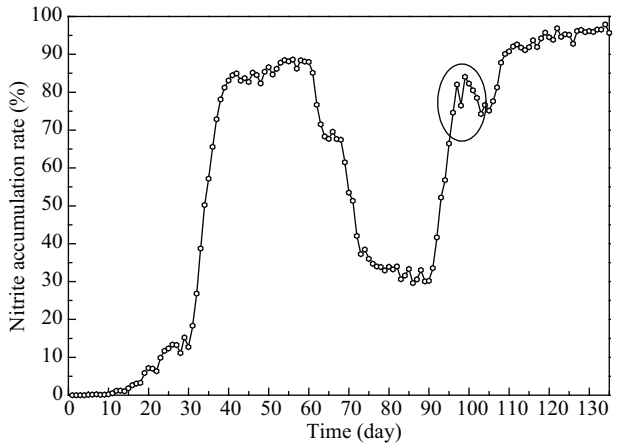

Fig. 7 Variations of nitrite accumulation rate at different alkalinity dosage ratios.

Bae, 2009); and it was found that NOB could be inhibited completely by impeding the respiration if the FA level was higher than 6.0 mg/L (Vadivelu et al., 2007). The inhibitory concentrations of FNA for AOB and NOB were 0.4 mg/L and 0.02 mg/L respectively (Vadivelu et al., 2006a, 2006b). Therefore, the activity of NOB could be suppressed by the double inhibitions of sensitivity difference to FA and FNA. A triple inhibition was formed when combined with low DO concentration. The pH of the influent was around 7.0 without sodium bicarbonate addition. Although the total ammonia in the influent was about 100 mg/L, the proportion of FA was small (**Fig. 3**, Eq. (5)), and was not up to the level to inhibit NOB, resulting in a low nitrite accumulation rate. When a small amount of sodium bicarbonate was added, pH in the influent rose and FA reached the concentration range that inhibited NOB, inducing the increase of nitrite accumulation rate. pH was decreased by the H^+ generated in the nitrification. The inhibition of FA toward NOB then disappeared due to the fall of pH, and the nitrite accumulation rate dropped. The biological activity of NOB was inhibited by the FA in the influent when the alkalinity dosage ratio was 1.5:1, leading to the increase of nitrite accumulation rate. The consumption of alkalinity during the nitrification reaction lowered the pH. The inhibitory effect of FA on NOB continued to weaken and even disappeared because of the continuous decrease of pH, and the nitrite accumulation rate declined accordingly. With the continuous diminution of pH, the proportion of FNA in the accumulated nitrite rose and arrived at the inhibitory level to NOB (Torà et al., 2010). Then nitrite accumulation no longer declined. When alkalinity addition was sufficient, FA was sufficient to inhibit NOB, and the nitrite accumulation rate was maintained at a high level (Park et al., 2010b). It was found that the inhibitory effects of FA and FNA on NOB

were temporary. When inhibition terminated, the activity of NOB revived.

3 Conclusions

pH affected the form of NH_4^+-N and nitrite present in aqueous solution, and there was a negative correlation between the two. Alkalinity plays an important role in terms of both growth substrate and environment for microorganisms, especially in establishing a balanced system for the growth of AOB and NOB in the control of nitritation.

The biomasses of AOB in suspended and attached activated sludge were 3.5 and 4 times higher than that of the original sludge. The distribution ratio of AOB to NOB was about 1.65 in the raw sludge, while the ratios for suspended and attached activated sludge were calculated to be 18.67 and 25.73, indicating that AOB was dominant in the MBBR.

Alkalinity was a vital factor in ammonia removal. NH_4^+-N removal efficiency rose from 13% to 88% when adequate sodium bicarbonate was added. NH_4^+-N removal increased first and then decreased, stabilizing at a low level when alkalinity addition was insufficient. A peak was observed in terms of NH_4^+ -N removal efficiency at each alkalinity dosage ratio when it increased from 0.5:1 to 1.5:1 stepwise. The reason for the peak removal needs to be further studied. Generally, NH_4^+-N removal efficiency increased with the increase of the alkalinity dosage ratio.

Nitrite accumulation could be achieved via the double inhibition of FA and FNA at low DO concentration when alkalinity addition was not sufficient. Initially, inhibition by FA toward NOB was employed to realize nitrite accumulation. The fall of pH enhanced the inhibitory effect of FNA on NOB along with the nitrifying process. Only the inhibitory effect of FA on NOB worked when alkalinity was adequate. The inhibitory effects of FA and FNA on NOB were temporary. When inhibition terminated, the activity of NOB revived.

Acknowledgments

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