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# Effect of anaerobic time on biological nitrogen removal in a modified SBR

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ABSTRACT

A new modified sequencing batch reactor (SBR) was proposed to treat wastewater. The modified SBR consists of 4 tanks with different anaerobic/anoxic/aerobic function. The organic substrate degradation and nitrification could occur sequentially in the different tank of the modified SBR. The dominant microorganisms grew in different tank to avoid the impact of high organic loadings. The results showed that the modified SBR was a high efficient reactor. The average $NH_4^+$-N and total nitrogen removal efficiency was 98 and 52, respectively. The ratio of influent $NH_4^+$-N/TN was equal approximately to TN removal efficiency, indicating that the TN removal efficiency was affected by the influent $NH_4^+$-N concentration. The longer anaerobic time was favored for the nitrogen removal. The optimal anaerobic time should be set at 1 h. The optimal ratio of aerobic/anaerobic time ($T_{O/A}$) was 0.5.

*Keywords:* Modified SBR; Nitrogen removal; Municipal wastewater; MLSS; EBPR

## 1. Introduction

The nitrogen and phosphate from wastewater promotes the eutrophication of lakes, rivers, and coasts, resulting in severe effects on the environment. Eutrophication is a major water quality problem all the world, which can cause algal blooms and disrupt the normal function of aquatic ecosystems [1]. Nitrogen and phosphorus removal from wastewater is one of the key strategies for preventing eutrophication. Stricter regulations have been applied to reduce

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eutrophication regarding nitrogen and phosphate discharge limit from wastewater.

The nitrogen removal from wastewater is of increasing importance. Various physiochemical and biological methods have been proposed to remove nitrogen compounds from wastewater. Biological nitrification and denitrification processes are usually used for wastewater treatment. These methods are applied much more frequently than physiochemical methods, due to their effectiveness and relatively low costs [2,3]. There are two key steps involved in nitrogen compounds removal from wastewater by nitrification and denitrification. Nitrification consists of a two-step mechanism that firstly ammonia is converted to nitrite, and secondly nitrite to nitrate using autotrophic bacteria such as Nitrosomonas and Nitrobacter species [4]. Denitrification includes heterotrophic and autotrophic processes. Biological nitrogen removal (BNR) processes have many types such as the sequencing batch reactor (SBR), the anaerobic/anoxic/oxic ($A_2O$) process, and the University of Cape Town process, etc [2,3,5,6]. The $A_2O$ process is used most widely among these BNR processes, which is a single sludge system consisting of sequential anaerobic/anoxic/aerobic phases. So far, some processes have achieved a high denitrification rate using the addition of an external carbon source. However, some problems from nitrifying bacteria being introduced in irregular amounts and concentrations have prevented substantial removal of total nitrogen [2]. Autotrophic ammonium oxidizing organisms are often out competed by other heterotrophic organisms due to their slow growth rates, which may affect the nitrification rate. The ammonia oxidation rate is also strongly affected by a variety of environmental factors, including dissolved oxygen (DO), pH, temperature, and substrate concentration. The immobilization of nitrifying bacteria using natural or synthetic materials as the support media can overcome these problems. These supporting materials must satisfy some requirements, including nontoxicity, retention of cellular survive, and stability in the medium. Immobilization of bacteria results in a relatively smaller reactor and provide some protection against temperature or toxic shocks [7].

The nitrogen removal could be achieved by three methods: (1) nitrate denitrification by providing anoxic or anaerobic phase, (2) operation at low DO concentration to encourage simultaneous nitrification and denitrification (SND), and (3) cyclic aeration (on/off) during the reaction phase [8]. It is very useful to combine both nitrification and denitrification in the same phase to reduce the carbon source requirement in treating municipal wastewater [9]. The conventional biological nitrogen removal involves separate aerobic and anoxic phases in separate reactors [10–12]. The SND has gained significant attention since the nitrification and denitrification occurs in one reactor under low DO condition [13]. Nitrogen removal via SND has been recognized as one strategy for saving energy consumption in biological wastewater treatment process [14].

The SBR is a widely used process for biological nutrient removal (nitrogen and phosphorus) from wastewater [15–17]. SBR has become increasingly popular in engineering applications for industrial wastewater treatment, such as poultry processing wastewater, brewery wastewater etc. [18,19]. One of the advantages of SBR process is its ability to treat wastewater in only one tank such as carbon substrate degradation, nitrogen and phosphorus removal [20–22]. Using one single SBR for treatment industrial wastewater, it is very difficult for the effluent quality to meet the discharge limits in China due to high COD and nitrogen concentrations [23].

SBR process is noted for its operational flexibility [24–26]. The SBR can remove both nitrogen and phosphorus in alternate anoxic/anaerobic/aerobic conditions [27–30]. The SBR process is normally operated on a fixed schedule of five phases, including loading, anoxic–anaerobic treatment, aerobic treatment, sedimentation, effluent extraction. Each phase has a fixed time without considering process requirements. This would not result in a highly efficient operation. Furthermore, a wrong timing may result in serious process problem [31]. The problem of SBR control is drawing increasing attention since the pioneering work of Oles started [32].

The flexibility of SBR requires a higher level of process control and automation management. An important characteristic of SBR is the special phase control on batch mode and step timing. The drawback of SBR is the intermittent operation with various sequences for carbon, nitrogen, and phosphorus removal. The SBR performance can be improved by the process development [33,34].

CASS and CAST processes were invented by Goranzy, based on SBR. However, these processes still had some disadvantages, especially considering phosphorus removal. A new modified SBR was proposed to overcome the disadvantages of the above reactors, which had different construction and operational mode compared with the previous MSBR described by Wu [35].

In this study, a novel modified SBR process (Fig. 1), which consisted of anaerobic/anoxic/aerobic phases, was introduced to remove nitrogen from wastewater. The objective of this study was threefold.

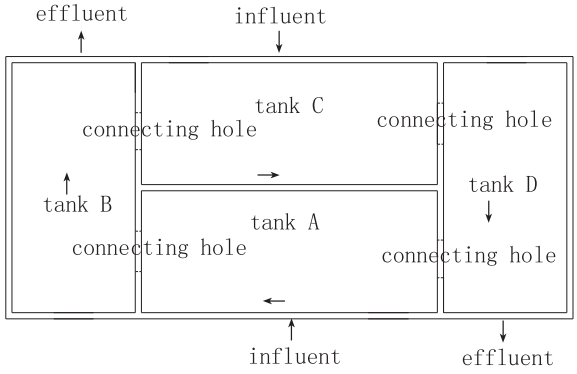


Fig. 1. Construction scheme of the modified SBR reactor.

Firstly, the performance of a modified SBR reactor was analyzed. Secondly, the relationship between $NH_4^+$-N and TN removal was investigated. Thirdly, the relationship between anaerobic time and TN removal was investigated.

## 2. Materials and methods

### 2.1. Experimental reactor

Experiments were carried out in a modified SBR reactor. The reactor was about 300 $m^3$, which was 9.6 m length, 8 m width, and 4.8 m depth (4 m effective water depth and 0.8 m high freeboard). It can treat urban wastewater of 500 $m^3$ every day. The hydraulic retention time (HRT) was 14 h. The air flow rate from the compressor was 28 $m^3 h^{-1}$. The water temperature was controlled at about 15°C in the reactor. The sludge retention time (SRT) in the reactor was maintained at 30 days by periodic waste sludge discharge. The DO and pH were continuously monitored by the sensors. The construction scheme of the modified SBR reactor is shown in Fig. 1. The seed sludge was 3,000 mg MLSS/L collected from the excess activated sludge of a conventional activated sludge process of a local wastewater treatment plant in Wuhan, China. The wastewater was fed into the reactor by a pump controlled with an electrode level switch. The discharge was carried out automatically using electric valves. Air was supplied by an electromagnetic blower controlled by a DO meter (OXY4150, Dalian, China).

### 2.2. Operating mode

The work cycle of the modified SBR reactor was 6 h, consisting of main body phase 1 (120 min), transitional phase 1 (60 min), main body phase 2 (120 min), and transitional phase 2 (60 min). During the main body phase 1, the influent was firstly added into A tank, then subsequently flowed through B and C tank with final effluent from D tank which was being used as a clarified tank in the main body phase 1 and transitional phase 1. The A, B, and C tank were supplied separately with alternating anoxic/anaerobic/aerobic condition. The influent could also be added into B and C tank according to operational requirement. During the transitional phase 1, the influent was added into the aerated C tank with the effluent from D tank. At the same time, the B tank stopped mixing and aeration to settle 1 h for the coming action as a clarified tank in the coming main body phase 2 and transitional phase 2.

During the main body phase 2, the influent was firstly added into C tank, subsequently flowed through D and A tank with final effluent from B tank which was being used as a clarified tank in the main body phase 2 and transitional phase 2. The C, D, and A tank were supplied separately with alternating anoxic/anaerobic/aerobic condition. The influent could also be added into D and A tank according to operational requirement. During the transitional phase 2, the influent was sent into the aerated A tank with the effluent from B tank. At the same time, the D tank stopped mixing and aeration to settle 1 h for the coming action as a clarified tank in the coming main body phase 1 and transitional phase 1.

### 2.3. Influent composition

The experiments were conducted using urban wastewater. The influent wastewater was obtained from a local wastewater treatment plant in Wuhan, China, which treated urban wastewater of 60,000 $m^3$/d. The average influent composition of $BOD_5$, COD, $NH_4^+$-N, TN, and TP was 135, 234, 17, 25, and 5 mg/L, respectively.

### 2.4. Analytical methods

The pH value was measured using a pH meter (HACH, Germany). The measurement of the mixed liquor suspended solids (MLSS), total nitrogen (TN), oxidized nitrogen ($NO_3^-$-N and $NO_2^-$-N), $NH_4^+$-N, and total phosphorus (TP) was carried out using a spectrophotometer (DR-5,000 HACH, Germany). The $BOD_5$, MLSS, MLVSS, TN, TP, $NH_4^+$-N, $NO_3^-$-N, and $NO_2^-$-N content was analyzed according to standard methods [36]. The chemical oxygen demand ($COD_{Cr}$) was measured with an oxidizer $K_2Cr_2O_7$ [37]. A dissolved oxygen meter (OXY4150, Dalian, China) connected to

a controlling computer was used to determine the dissolved oxygen (DO) concentration online. The microbe species in the activated sludge was observed using an optic microscope.

## 3. Results

### 3.1. $NH_4^+$-N, TP, TN, COD removal

The reactor was acclimatized for about 60 days prior to monitoring. All the results were obtained at steady state in the reactor. The changes of $NH_4^+$-N, TP, TN, and COD during one anaerobic and aerobic cycle in the modified SBR were observed for one year. In the anaerobic phase, the COD decreased slowly within 60 min, and the phosphorus release was observed. In the aerobic phase, the COD decreased quickly within 30 min, the phosphorus uptake was observed. It was inferred that the internally stored PHA was oxidized for cell growth, phosphorus uptake, and glycogen synthesis due to no external carbon source. In the aerobic phase, the TP and $NH_4^+$-N concentrations decreased quickly with the increase in $NO_3^-$-N concentration. The $NO_2^-$-N concentration was less than 0.02 mg/L showing that the $NO_2^-$-N was not accumulated in the modified SBR. At the end of aerobic phase, the TP concentration decreased to the lowest, while the $NO_3^-$-N concentration increased to the highest. The pH in the modified SBR was up from 7.1 to 7.5 between the beginning and end of anaerobic phase. The pH decreased rapidly from 7.5 to 7.1 within 1 h when aerobic phase started. It was inferred that the pH decrease was due to the production of $H^+$ by nitrification with low neutralization capacity of wastewater.

$NH_4^+$-N, TP, TN, and COD removal efficiency was summarized as follows. The average effluent COD and removal efficiency was 35 mg/L and 85 %. The effluent $NH_4^+$-N was about 1.4 mg/L during most of the operational period. The average $NH_4^+$-N removal efficiency was more than 98%. The effluent TN and removal efficiency was below 12 mg/L and 52%. Although the effluent TN concentration had met the discharge limits (20 mg/L) in China, TN removal efficiency was not satisfied. The average effluent TP and removal efficiency was 0.75 mg/L and 85%.

### 3.2. Relationship between $NH_4^+$-N and TN removal

#### 3.2.1. Analysis of $NH_4^+$-N and TN in the influent

Influent $NH_4^+$-N and TN concentration was measured continuously, as shown in Fig. 2. The influent $NH_4^+$-N and TN fluctuated in a wide scope between 10–20 mg/L $NH_4^+$-N and 17–30 mg/L TN, respectively. From Fig. 2, it can be seen that the average influent $NH_4^+$-N concentration was 17 mg/L, the average influent TN concentration was about 24.8 mg/L. So, it could be inferred that the average ratio of influent $NH_4^+$-N to TN was 68%.

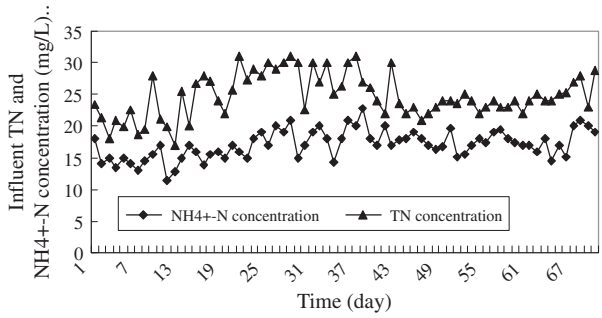


Fig. 2. Influent $NH_4^+$-N and TN concentration.

#### 3.2.2. Analysis of $NH_4^+$-N and TN in the reactor

The $NH_4^+$-N and TN concentration in the C tank was measured continuously at the end of aerobic phase, as shown in Fig. 3. By analyzing $NH_4^+$-N and TN concentration in the C tank for many times, the $NH_4^+$-N and TN fluctuated in a small scope between 1.5–2.13 mg/L $NH_4^+$-N and 17.3–20.5 mg/L TN, respectively. As seen in Fig. 3, the average $NH_4^+$-N and TN concentration was 1.9 and 19 mg/L in the C tank at the end of aerobic phase. Therefore, it could be inferred that the average ratio of the $NH_4^+$-N to TN was 10% in the reactor, that is, the residual 90% TN consisted of organic nitrogen, $NO_3^-$, and $NO_2^-$.

#### 3.2.3. Analysis of $NH_4^+$-N and TN in the effluent

The $NH_4^+$-N and TN concentration in the effluent was measured continuously, as shown in Fig. 4. By

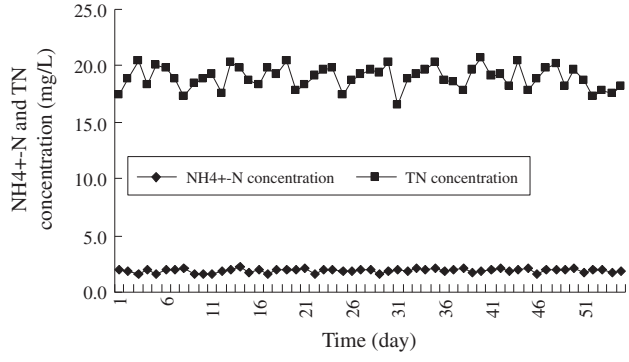


Fig. 3. $NH_4^+$-N and TN concentration in the reactor.

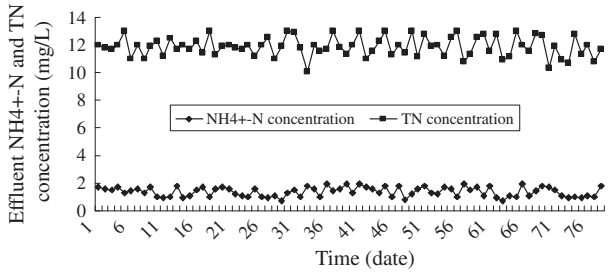


Fig. 4. Effluent $NH_4^+$-N and TN concentration.

analyzing effluent $NH_4^+$-N and TN concentration for many times, the effluent $NH_4^+$-N and TN fluctuated in a small scope between 0.7–1.9 mg/L $NH_4^+$-N and 11–13 mg/L TN, respectively. From Fig. 4, the average effluent $NH_4^+$-N and TN concentration was about 1.4 and 11.8 mg/L. Therefore, it could be inferred that the average ratio of the effluent $NH_4^+$-N to TN was 12%.

On the base of the above results, it was inferred that the value of the influent $NH_4^+$-N/TN ratio (68%) minus the effluent $NH_4^+$-N/TN ratio (12%) was equal approximately to TN removal efficiency. TN removal in the reactor was in fact equal to the influent $NH_4^+$-N removal. The influent organic nitrogen was approximately equal to the effluent organic nitrogen, showing that organic nitrogen removal in the reactor was poor. The TN removal efficiency was affected by the influent $NH_4^+$-N concentration.

### 3.3. Effect of anaerobic time on TN removal

The experimental results showed that the average TN removal efficiency was 50, 55, 67, and 70% with the anaerobic time of 20, 45, 60, and 90 min, respectively. The relationship between the TN removal efficiency and anaerobic time was shown in Fig. 5. From Fig. 5, two simulation curves were obtained through mathematic analysis showed in the following Eqs. (1) and (2). The result showed that the Eq. (1) was better than Eq. (2) in accuracy.

$$y = -0.5x^2 + 9.7x + 40 \quad R^2 = 0.9531 \tag{1}$$

$$y = 15.217\mathrm{Ln}(x) + 48.41 \quad R^2 = 0.9196 \tag{2}$$

### 3.4. Effect of anaerobic time on $NH_4^+$-N concentration

The relationship between $NH_4^+$-N concentration in the reactor and anaerobic time was showed in Fig. 6. A simulation curves was obtained through mathematic analysis, showed in Eq. (3). The experimental results showed that the average $NH_4^+$-N concentration in the reactor could be improved by the increase of anaerobic time. If the average $NH_4^+$-N concentration in the reactor could be improved, it would result in the increase of the TN removal efficiency according to the above conclusion.

$$y = 0.3344\mathrm{Ln}(x) + 0.4093 \quad R^2 = 0.9899 \tag{3}$$

### 3.5. Mass balance analysis on influent and effluent nitrogen

Nitrogen compositions consist of $NH_4^+$-N, $NO_2^-$-N, $NO_3^-$-N and organic nitrogen. To analyze nitrogen balance, the following calculation was performed.

In the influent, the average $NH_4^+$-N concentration was 17 mg/L, the average $NO_2^-$-N concentration was

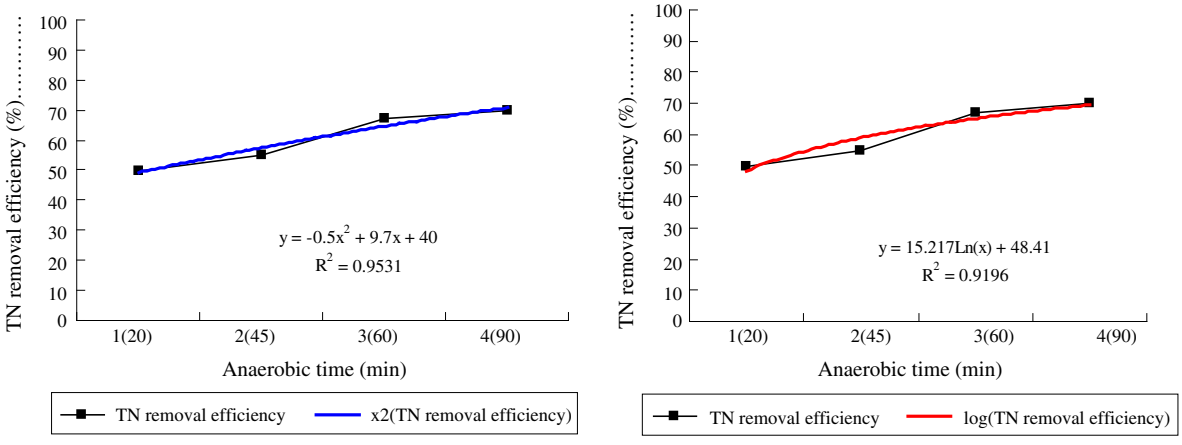


Fig. 5. Relationship between the TN removal efficiency and anaerobic time. $X = 1$, 2, 3, and 4 according to anaerobic time 20, 45, 60, and 40 min.

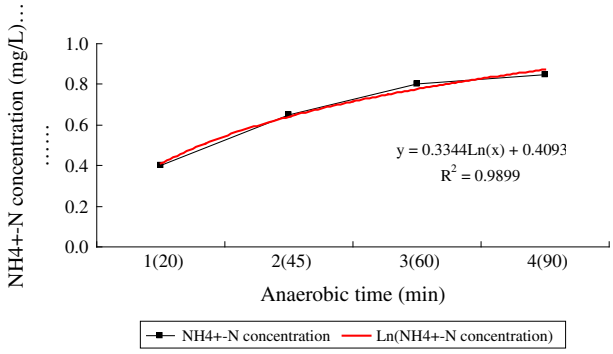


Fig. 6. Relationship between $NH_4^+$-N concentration in the reactor and anaerobic time. $X = 1$, 2, 3, and 4 according to anaerobic time 20, 45, 60, and 40 min.

0.01 mg/L, the average $NO_3^-$-N concentration was 0.2 mg/L, and the average TN concentration was 25 mg/L. Therefore, it could be inferred that the influent organic nitrogen concentration was 7.6 mg/L. $NH_4^+$-N/TN was 68%, $NO_2^-$-N/TN was about 0, $NO_3^-$-N/TN was 2%, and organic nitrogen/TN was 30%.

In the effluent, the average $NH_4^+$-N concentration was 1.4 mg/L, the average $NO_2^-$-N concentration was 0.08 mg/L, the average $NO_3^-$-N concentrations was 5.6 mg/L, and the average TN concentration was 12 mg/L. Therefore, it could be inferred that the effluent organic nitrogen concentration was 4.92 mg/L, $NH_4^+$-N/TN was 12%, $NO_2^-$-N/TN was about 0, $NO_3^-$-N/TN was 47%, and organic nitrogen/TN was 41%.

The influent organic nitrogen concentration was 7.6 mg/L, the effluent organic nitrogen concentration was 4.92 mg/L. It showed that the ability of organic nitrogen removal was poor in the modified SBR. TN removal was mainly from $NH_4^+$-N removal. It showed that the influent $NH_4^+$-N/TN ratio was equal approximately to TN removal efficiency.

Influent nitrogen compositions were showed in Fig. 7. Effluent nitrogen compositions were showed in Fig. 8.

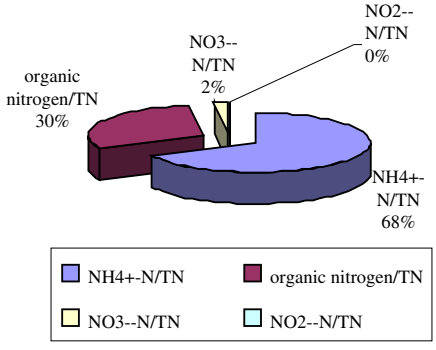


Fig. 7. Influent nitrogen compositions.

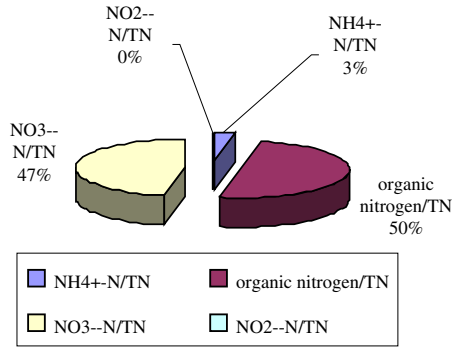


Fig. 8. Effluent nitrogen compositions.

### 3.6. Effect of aerobic/anaerobic time ratio on nitrogen removal

Every tank in the reactor was aerated intermittently. The ratio of aerobic/anaerobic time (i.e., $T_{O/A}$) affected nitrogen removal efficiency. The relationship between $T_{O/A}$ and nitrogen removal efficiency was investigated. $T_{O/A}$ was adjusted four times for finding the optimal $T_{O/A}$. The reactor was operated steadily seven days at various $T_{O/A}$. To simplify object, $T_{O/A}$ of tank C was analyzed. The operational conditions of four various $T_{O/A}$ were shown in Table 1.

The nitrogen removal efficiency at various $T_{O/A}$ was shown in Fig. 9. The nitrogen removal efficiency was 0.66, 0.63, 0.57, and 0.5 with various $T_{O/A}$ at 0.5, 2.6, 3.5, and 5.0, respectively.

## 4. Discussion

The modified SBR had a special structure consisting of 4 tanks with anaerobic/anoxic/aerobic function. By controlling the operational conditions, organic substrate degradation and nitrification could occur sequentially in every tank of the modified SBR. The dominant microorganisms grew in respective tank, which avoided the negative impact of high organic loadings on nitrification and maintained system stability.

### 4.1. $NH_4^+$-N removal

$NH_4^+$-N removal efficiency was up to 98%. The impossible reason was that the longer aerobic time resulted in the nitrifying bacteria from the activated sludge growth well, which could convert most of $NH_4^+$-N to $NO_3^-$-N.

### 4.2. TN removal

From the operational results, the average TN removal was only 52%. Therefore, TN removal

Table 1
Operational conditions of four various $T_{O/A}$

| Item | Condition 1 | Condition 2 | Condition 3 | Condition 4 |
|---|---|---|---|---|
| Water temperature (℃) | 15 | 15 | 15 | 15 |
| Average MLSS | 3,000 | 3,000 | 3,000 | 3,000 |
| MLVSS/MLSS | 0.48 | 0.48 | 0.48 | 0.48 |
| $T_{O/A}$ | 0.5 | 2.6 | 3.5 | 5.0 |

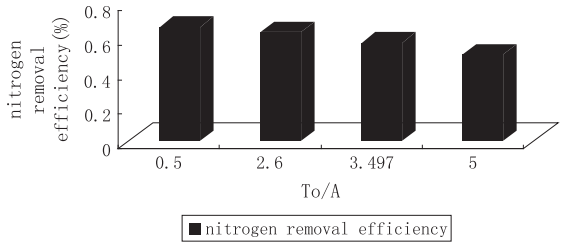


Fig. 9. Nitrogen removal efficiency at various $T_{O/A}$.

efficiency was poor. The impossible reason was that the longer aerobic time resulted in more conversion of $NH_4^+$-N into $NO_3^-$-N. However, the short anaerobic time could not change more $NO_3^-$-N into $N_2$, resulting in a great amount of $NO_3^-$-N accumulated in wastewater.

The experimental results showed that the conversion rate of the organic nitrogen to $NH_4^+$-N would become slow after 1 h anaerobic phase. The more the organic nitrogen was changed into $NH_4^+$-N, the higher the TN removal efficiency would be. If the TN removal efficiency is expected more than 90%, it can be realized by improving $NH_4^+$-N/TN up to 90%. For most of urban wastewater, it is not necessary to achieve TN removal efficiency up to 90%, because it would probably expend more aerobic time to reach it, but the increasing rate of TN removal is limited. After taking into account the phosphorus and TN removal together, the optimal anaerobic time should be set at 1 h. Under this condition, the reactor efficiency is higher, the reactor construction cost is lower, and the reactor power is saved.

### 4.3. $T_{O/A}$ and nitrogen removal efficiency

The experimental result showed that the nitrogen removal efficiency would become lower and lower when the aerobic time was higher than the half of anaerobic time. The optimal $T_{O/A}$ was 0.5, and the nitrogen removal efficiency was 66%. The possible cause was that the anaerobic time was too short to let denitrification bacteria growth well. The denitrification bacteria could not synthesize enough poly β-hydroxybutyric acid (PHB) inside bacteria, so the denitrification bacteria could not survive under aerobic conditions. Furthermore, if the denitrification bacteria were short of PHB inside bacteria, it would result in self-oxidation of bacteria. Consequently, the nitrogen removal efficiency became poor when $T_{O/A}$ was over 0.5. When $T_{O/A}$ was equal to 5, the nitrogen removal efficiency was 50%. The experimental result showed that the anaerobic time was very important for denitrification.

## 5. Conclusions

For municipal wastewater, the experiment obtained the following results under the proper dissolved oxygen and anaerobic time conditions.

(1) The modified SBR had a special structure consisting of four tanks with different anaerobic/anoxic/aerobic function. By controlling the operational conditions, organic substrate degradation and nitrification could occur sequentially in the different tank of the modified SBR. The dominant microorganisms grew in respective tank, which avoided the negative impact of high organic loadings on nitrification and maintained system stability.
(2) This reactor was an integrated bioreactor with flexible management and low operational cost. The effluent quality of this reactor was very good. The most effluent $NH_4^+$-N concentration was less than 1.4 mg/L. The average $NH_4^+$-N removal efficiency exceeded 98%. The effluent TN concentrations were less than 12 mg/L. The average TN removal efficiency was 52%. The average effluent TP concentration was 0.75 mg/L. The average TP removal efficiency was 85%. The average effluent COD concentration was 35 mg/L. The average COD removal efficiency was 85%.
(3) The influent $NH_4^+$-N/TN ratio was equal approximately to TN removal efficiency. The influent organic nitrogen was about equal to the effluent organic nitrogen. TN removal efficiency was affected by influent $NH_4^+$-N.

(4) The TN removal efficiency could be improved by the prolonged anaerobic time. The optimal anaerobic time was 1 h. Under this condition, the TN removal efficiency achieved 66%; the effluent TN could meet the discharging limits in China, and the reactor power was saved.
(5) A longer aerobic time was disadvantageous to nitrogen removal under the $T_{O/A}$ more than 0.5 condition. The optimal $T_{O/A}$ was 0.5.

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## References

[1] Eun-Tae Lim, Gwi-Taek Jeong, Sung-Hun Bhang, Seok-Hwan Park, Don-Hee Park, Evaluation of pilot-scale modified $A^2O$ processes for the removal of nitrogen compounds from sewage, Bioresour. Technol. 100 (2009) 6149–6154.
[2] Y.Z. Peng, X.L. Wang, B.K. Li, Anoxic biological phosphorus uptake and the effect of excessive aeration on biological phosphorus removal in the $A_2O$ process, Desalination 189 (2006) 155–164.
[3] C. Gabaldon, M. Izquierdo, V. Martmez-Soria, P. Marzal, J.M. Penya-roja, F.J. Alvarez-Hornos, Biological nitrate removal from wastewater of a metal finishing industry, J. Hazard. Mater. 148 (2007) 485–490.
[4] P. Noophan, S. Sripiboon, M. Damrongsri, J. Munakata-Marr, Anaerobic ammonium oxidation by Nitrosomonas spp. and anammox bacteria in a sequencing batch reactor, J. Envir on. Manage. 90 (2009) 967–972.
[5] D. Kim, T.S. Kim, H.D. Ryu, S.I. Lee, Treatment of low carbon-to-nitrogen wastewater using two-stage sequencing batch reactor with independent nitrification, Process Biochem. 43 (2008) 406–413.
[6] H.D. Ryu, D. Kim, H.E. Lim, S.I. Lee, Nitrogen removal from low carbon to nitrogen wastewater in four-stage biological aerated filter system, Process Biochem. 43 (2008) 729–735.
[7] L.M.C. Daniel, E.P. Pozzi, E. Foresti, F.A. Chinalia, Removal of ammonium via simultaneous nitrification–denitrification nitrite-shortcut in a single packed bed batch reactor, Bioresour. Technol. 100 (2009) 1100–1107.
[8] Eddy Metcalf, Wastewater Engineering, Treatment & Reuse, 4th ed., McGrow-Hill, Boston, MA, 2003.
[9] Yousef Rahimi, Ali Torabian, Naser Mehrdadi, Behzad Shahmoradi, Simultaneous nitrification–denitrification and phosphorus removal in a fixed bed sequencing batch reactor (FBSBR), J. Hazard. Mater. 185 (2011) 852–857.
[10] X. Metcalf, X. Eddy, Wastewater Engineering Treatment Disposal and Reuse, third ed., McGraw-Hill, New York, NY, 1991. pp. 429–433.
[11] T. Panswad, C. Anan, Specific oxygen, ammonia, and nitrate uptake rates of a biological nutrient removal process treating elevated salinity wastewater, Bioresour. Technol. 70 (1999) 237–243.
[12] D. Mulkerrins, E. O'Connor, B. Lawlee, P. Barton, A. Dobson, Assessing the feasibility of achieving biological nutrient removal from wastewater at an Irish food processing factory, Bioresour. Technol. 91(2) (2004) 207–214.
[13] E. Von Müch, P. Lant, J. Keller, Simultaneous nitrification and denitrifiation in bench-scale sequencing bath reactors, Water Res. 30 (1996) 277–284.
[14] Li Hongjing, Chen Yinguang, Gu Guowei, The effect of propionic to acetic acid ratio on anaerobic–aerobic (low dissolved oxygen) biological phosphorus and nitrogen removal, Bioresour. Technol. 99 (2008) 4400–4407.
[15] S. Morling, E. Plaza, Biological nitrogen removal at low water temperatures — long term experience, Desalin. Water Treat. 25 (2011) 226–232.
[16] Andrea Blšťáková, Igor Bodík, Stanislav Sedláček, Miloslav Drtil, Laboratory operation of MBR and SBR models with selected inhibitors of nitrification, Desalin. Water Treat. 35 (2011) 185–194.
[17] Katarzyna Bernat, Dorota Kulikowska, Magdalena Zielińska, Agnieszka Cydzik- Kwiatkowska, Irena Wojnowska-Baryła, The treatment of anaerobic digester supernatant by combined partial ammonium oxidation and denitrifi cation, Desalin. Water Treat. 37 (2012) 223–229.
[18] Wei Zeng, Yongzhen Peng, Shuying Wang, Startup operation and process control of a two-stage sequencing batch reactor (TSSBR) for biological nitrogen removal via nitrite, Desalin. Water Treat. 1 (2009) 318–325.
[19] Wei Zeng, Yue Zhang, Lei Li, Yongzhen Peng, Shuying Wang, Simultaneous nitritation and denitritation of domestic wastewater without addition of external carbon sources at limited aeration and normal temperatures, Desalin. Water Treat. 21 (2010) 210–219.
[20] E. Lai, S. Senkpiel, D. Solley, J. Keller, Nitrogen removal of high strength wastewater via nitritation/denitritation using a sequencing batch reactor, Water Sci. Tech. 50(10) (2004) 27–33.
[21] V. Pambrun, E. Paul, M. Spérandio, Treatment of nitrogen and phosphorus in highly concentrated effluent in SBR and SBBR processes, Water Sci. Tech. 50(6) (2004) 269–276.
[22] C. Fux, S. Velten, V. Carozzi, D. Solley, J. Keller, Efficient and stable nitritation and denitritation of ammonium-rich sludge dewatering liquor using an SBR with continuous loading, Water Res. 40 (2006) 2765–2775.
[23] Qiuyan Yuan, Jan Oleszkiewicz, Selection and enrichment of denitrifying phosphorus accumulating organisms in activated sludge, Desalin. Water Treat. 22 (2010) 72–77.
[24] R.L. Irvine, L.H. Ketchum, Jr., Sequencing batch reactors for biological wastewater treatment, CRC Crit. Rev. Environ. Control 18 (1989) 255–294.
[25] J.P. Kerrn-Jesperson, M. Henze, Biological phosphorus removal from wastewater by aerobic-anoxic sequencing batch reactors, Water Res. 27 (1993) 617–624.
[26] N. Artan, P. Wilderer, D. Orhon, E. Morgenroth, N. ÖzgÜr, The mechanism and design of sequencing batch reactor systems for nutrient removal—the state of the art, Water Sci. Technol. 43 (2001) 53–60.
[27] G.J.F. Smolders, M.C.M. van Loosdrecht, J.J. Heijnen, A metabolic model for the biological phosphorus removal process, Water Sci. Technol. 31(2) (1995) 79–93.
[28] E. Murnleitner, T. Kuba, M.C.M. van Loosdrecht, J.J. Heijnen, An integrated metabolic model for the aerobic and denitrifying biological phosphorus removal, Biotechnol. Bioeng. 54 (1997) 434–450.
[29] F. Carta, J.J. Beun, M.C.M. van Loosdrecht, J.J. Heijnen, Simultaneous storage and degradation of PHB and glycogen in activated sludge cultures, Water Res. 35 (2001) 2693–2701.
[30] J.J. Beun, K. Dircks, M.C.M. van Loosdrecht, J.J. Heijnen, Poly b-hydroxybutyrate metabolism in dynamically fed mixed microbial cultures, Water Res. 36 (2002) 1167–1180.

[31] S. Marsili-Libelli, Control of SBR switching by fuzzy pattern recognition, Water Res. 40 (2006) 1095–1107.
[32] J. Oles, P.A. Wilderer, Computer aided design of sequencing batch reactors based on the IAWPRC activated sludge model, Water Sci. Technol. 23 (1991) 1087–1095.
[33] C.S. Ra, K.V. Lo, J.S. Shin, J.S. Oh, B.J. Hong, Biological nutrient removal with an internal organic carbon source in piggery wastewater treatment, Water Res. 34(3) (2000) 965–973.
[34] R.F. Yu, S.L. Lia, C.N. Chang, W.Y. Cheng, Applying real-time control to enhance the performance of nitrogen removal in the continuous-flow SBR system, Water Res. 38(3) (1998) 271–280.
[35] W. Wu, P. Timpany, B. Dawson, Simulation and applications of a novel modified SBR system for biological nutrient removal, Water Sci. Technol. 43(3) (2001) 215–222.
[36] APHA, Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, 1999.
[37] Li Jun, Tao Tao, Li Xue-bin, Zuo Jiao-lan, Li Tong, Lu Jin, Li Shu-hui, Chen Li-zhen, Xia Chun-yang, Liu Yong, Wang Yan-li, A spectrophotometric method for determination of chemical oxygen demand using home-made reagents, Desalination 239 (2009) 139–145.