Performance of sequencing batch biofilm reactors with different control systems in treating synthetic municipal wastewater

Yunxiao Jin\textsuperscript{a,b}, Dahu Ding\textsuperscript{a}, Chuanping Feng\textsuperscript{a,}* Shuang Tong\textsuperscript{a}, Takashi Suemura\textsuperscript{c}, Feng Zhang\textsuperscript{a}

\textsuperscript{a} School of Water Resources and Environment, China University of Geosciences, No. 29 Xueyuan Road, Beijing 100083, China
\textsuperscript{b} Department of Civil Engineering, Luoyang Institute of Science and Technology, No. 90 Wangcheng Road, Luoyang 471023, China
\textsuperscript{c} Rtech Co. Advanced Logic System, Ibaraki, Japan

\begin{abstract}
This study aimed to evaluate the performances of sequencing batch biofilm reactors (SBBRs) in removing nitrogen and phosphorus from synthetic municipal wastewater with different carbon to total nitrogen (C/N) ratios. The effect of control systems, including an intelligent control system (ICS) and conventional timer control system (TCS) on the performance of SBBRs was also investigated. When C/N ratios were 10.0, 5.0 and 3.3, the average COD removal efficiencies in the ICS-SBBR reached 87.7\%, 92.3\% and 97.6\%, while total phosphorus (TP) removals reached 95.0\%, 97.0\% and 97.2\%. When the C/N ratio was 5.0, the TN removal efficiency was 81.0\% under ICS and 65.4\% under TCS. Moreover, compared with TCS-SBBR, both reaction time and aeration time were shortened by 180 min and 157 min, respectively, in the ICS-SBBR. Therefore, the ICS-SBBR has potential in practical applications for significant nitrogen and phosphorus removal and energy savings.
\end{abstract}

1. Introduction

Nitrogen and phosphorus have become the key factors leading to eutrophication of receiving waters. In order to decrease the nitrogen and phosphorus, control of pollution sources and reducing discharge are the most fundamental ways to prevent water eutrophication (Zou et al., 2006). Therefore, increasingly stringent discharge limits for nitrogen and phosphorus in many countries are creating an urgent need for technological solutions (Di Iaconi et al., 2003; Ge et al., 2010).

In general, because of their ability to achieve simultaneous nitrogen and phosphorus removal, biological methods play an important role in treating municipal wastewater, such as the conventional suspended-growth activated sludge process, oxidation ditch process, and anaerobic/anoxic/oxic (A/A/O) process (Rogers et al., 2006). These traditional methods usually consist of a combination of aerobic nitrification and anaerobic denitrification, which means that at least two separate reactors must be constructed to remove nitrogen and phosphorus (Xia et al., 2008). Therefore, new sustainable processes are being developed to decrease the construction, operation and management costs.

Biofilm reactors take advantage of biofilms to remove nitrogen and phosphorus in a single bioreactor (Fu et al., 2010; Wilderer and McSwain, 2004; Zhang et al., 2009). Compared with the suspended-growth activated sludge process, biofilm reactors offer advantages such as land and energy savings, greater biomass concentration, flexible operation, lower sensitivity to toxicity and sludge production, greater volumetric loads (Rogers and Zhan, 2003). The sequencing batch biofilm reactor (SBBR), which uses alternating anoxic and aerobic conditions, has been proven feasible for nitrogen and phosphorus removal (Fu et al., 2010). Furthermore, the SBBR offers an anoxic microzone in the inner layers of the biofilm due to a dissolved oxygen (DO) gradient during the aeration phase (Choi et al., 2008). Therefore, simultaneous nitrification and denitrification (SND) could be achieved, with nitrification on the surface of the biofilm and denitrification in the inner layers (Cassidy et al., 2000). In addition, denitrifying phosphorus removal can occur in the anoxic microzone (Choi et al., 2008). Accordingly, the SBBR has been adopted to remove nitrogen and phosphorus simultaneously from many kinds of wastewater (Di Iaconi et al., 2004).

Although the SBBR can obtain high pollutant removal performance, its operation and management are complex. The operation mode plays an important role in application of SBBR. Some researchers (Suntud Sirianuntapiboon, 2006; Kim et al., 2008) initially used timers to control the SBBR operation, and then more complicated programmable logical controller (PLC) was developed later (Goh et al., 2009; Xia et al., 2008; Zhang et al., 2009). However, the timer and PLC controls systems were based on operation time, and did not involve temperature. During the reaction phase, the reactor was aerated continuously, resulting in a low oxygen utilization rate (OUR) and high energy consumption. DO concentration and temperature (T) were important parameters that
affected the metabolic activities of the microorganisms. Do Canto et al. (2008) indicated that DO concentration and temperature might affect nitrifying bacteria growth and activity. Peng et al. (2007) evaluated the feasibility of partial nitrification from raw domestic wastewater at ambient temperature by aeration control only and observed that a limited airflow rate would eventually induce only nitrification to nitrite, and not further to nitrate, because of oxygen deficiency in the reactor.

An intelligent control system (ICS), based on both DO concentration and T in the wastewater, was developed in this study and adopted to control the SBBR for treating synthetic municipal wastewater. In order to investigate the nitrogen and phosphorus removal performances, two laboratory-scale SBBRs, controlled by ICS and timer controlling system (TCS), respectively, were used to treat synthetic municipal wastewater with different C/N ratios (10.0, 5.0, 3.3).

2. Methods

2.1. Experimental set-up

As shown in Fig. 1, two acrylic reactors, with identical dimensions of $400 \times 250 \times 300$ mm ($L \times W \times H$) and total working volume 20 L, were used in this study. Multiple cylinders (diameter 40 mm, height 260 mm) with many holes (diameter 0.5 mm) evenly distributed on their surfaces were used as water collectors in the reactor. Fiber threads were attached to the cylinder to serve as biofilm carriers. The ICS consisted of a PC, PLC and control software.

The effluent was pumped from a pipe on the top of the cylinder. Oxygen was introduced into the reactor by an air compressor and distributed through fine-bubble diffuser stones at an airflow rate of 150 L/h. A magnetic circulation pump was used to control water temperature and obtain a homogeneous distribution of fiber threads by circulating the wastewater through a thermostatic bath. In order to evaluate the effects of two control systems on the performance of SBBRs, the water temperatures in the two bioreactors were both maintained at $25 \pm 1^\circ$C during the experiments.

The ICS was described in an earlier publication (Ding et al., 2011). Different DO concentrations had remarkable effects on the respiratory rate of the microorganisms under the same temperature. Therefore, temperature and DO concentration were both used as controlling factors in the ICS. The ICS based on the temperature and the slope of the DO concentration curve, giving a schedule for the nitrification and denitrification phase. The procedure is as follows: DO concentration test \rightarrow calculation of the oxygen consumption in the aeration phase \rightarrow calculation of oxygen consumption in the next phase \rightarrow air compressor control. An operation cycle contained one calculation period and several reaction periods. During each reaction period, the bioreactor was first aerated ($T_1$) and then non-aerated ($T_2$) and the total time for each reaction period was constant at 120 min. However, $T_1$ and $T_2$ during different reaction periods varied with the temperature and the DO concentration in the bioreactor.

After wastewater filling, a calculation period was carried out in the ICS-SBBR, which included an aerobic phase and a subsequent anoxic phase. After 30 min aeration, if the DO concentration in the reactor was higher than the minimum DO value ($DO_{min}$), the air compressor stopped. Otherwise, the air compressor would keep working for another 10 min until the DO concentration increased to $DO_{min}$. At the end of the anoxic phase (30 min), if the DO concentration was lower than $DO_{min}$, the air compressor would start, otherwise the reactor was kept anoxic until the DO concentration decreased to $DO_{min}$. During the calculation period, the ICS gave a schedule for the aerobic and anoxic phases for the next period (120 min) based on the slope of the DO concentration curve in the previous period.

2.2. Biofilm carrier

Considering their high specific area and low price, as found in a previous study (Wang et al., 2009a), fiber threads with a specific surface area of 2800 $m^2/m^3$ and porosity of 98%, were used as biofilm carriers. The carrier filling ratio was 10% (v/v). Just as for plants in water, the rough surfaces of the fiber thread were beneficial to the strong adsorption and growth of organisms. The fiber threads could also serve as filter media to minimize the concentration of suspended solids in the effluent. Therefore, the time for settling was reduced and the volume of the bioreactor was decreased.

2.3. Synthetic wastewater

Synthetic wastewater was prepared based on the characteristics of Chinese municipal wastewater, the composition of which was as follows (concentrations in mg/L): Glucose ($C_6H_{12}O_6$) (332), NH$_4$Cl (114, 213 and 342 at initial C/N ratios of around 10.0, 5.0 and 3.3, respectively), KH$_2$PO$_4$ (21.95), ZnCl$_2$ (50), MgSO$_4$ (50), and a 1 ml trace element mixture, consisting of 0.075 g CaCl$_2$, 0.04 g CuCl$_2$·H$_2$O, 0.048 g NiCl$_2$·6H$_2$O, 0.044 g FeSO$_4$·7H$_2$O and 0.120 g H$_3$BO$_3$. 100 mg/L NaHCO$_3$ was added to maintain the pH of the synthetic wastewater at 6.8–7.2. All chemicals and reagents used to prepare the synthetic wastewater were of analytical grade.

![Fig. 1. Schematic diagram of two SBBRs](image-url)
Three initial influent C/N ratios (10.0, 5.0 and 3.3) were investigated. Each bioreactor was filled with 20 L of synthetic wastewater.

2.4. Analytical methods

All water samples were filtered through a 0.45 μm membrane and then NH₃–N, total nitrogen (TN), nitrate (NO₃–N), nitrite (NO₂–N), and total phosphorus (TP) concentrations were determined by ultraviolet spectrophotometer (HACH, DR 5000) according to Standard Methods (S.E.P.A, 2002). The chemical oxygen demand (COD) was measured following the closed reflux titration with potassium dichromate according to Standard Methods (S.E.P.A, 2002). Temperature and DO concentration were continuously measured online using a DO detector (HACH SC100, USA). The pH was determined with a portable digital pH meter (LIDA 220, China).

The thicknesses of biofilms in the ICS and the TCS were examined on the fiber threads carrier by using a vernier caliper at the three depths of 40, 120 and 240 mm from the bottom of reactor. Three measurements were made in order to obtain the average biofilm thickness of each depth.

Efficiency of the SND process (ESND) was calculated according to Eq. (1) (Xia et al., 2008):

\[
ESND = 1 - \frac{NO_{\text{remained}} - NH_{4}^{+} \text{oxidized}}{NH_{4}^{+} \text{oxidized}} \times 100
\]

where NO\text{remained} refers to the NO\text{remained} concentration remaining in the effluent and NH\text{oxidized} to the NH\text{oxidized} oxidized during the reaction.

2.5. Statistical analysis method

Each experiment was repeated three times. All the data were subjected to analysis of variance (ANOVA) using Origin 8.0. Statistical significance was tested using the least significant difference (LSD) at the p < 0.05 level. The statistical results shown in the text are standard errors of the mean computations and the comparisons presented in figures are standard deviation.

2.6. Operation of ICS-SBBR and TCS-SBBR

The reactors were inoculated with activated sludge taken from QingHe Municipal Wastewater Treatment Plant, Beijing, China. The mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were 8420 and 5280 mg/L, respectively. The value of MLVSS/MLSS was 0.63. After settling for 1 day, 5 L of activated sludge was added into each reactor to domesticate the sludge. The characteristics of the synthetic wastewater used in this start-up period were: COD (300 mg/L), TN (30 mg/L) and TP (5 mg/L). The operation strategies in the two SBBRs were: fill (2 min)—anaerobic phase (3 h)—aeration phase (9 h)—settle (10 min)—draw (47 min) – aeration (5 min) – non-aeration (115 min) – aeration (10 min) – non-aeration (120 min) – aeration (8 min) – non-aeration (52 min).

Both bioreactors were operated from 9 May 2009 to 30 August 2010. The experimental data were obtained from 1 November 2009 to 31 January 2010. The sludge retention time (SRT) was maintained at around 26 days and the two bioreactors ran for 15, 20 and 20 days at C/N ratios of 10.0, 5.0 and 3.3, respectively. The COD and TP concentrations in the influent were around 300 and 5 mg/L and the three C/N ratios were tested through adjusting the concentration of nitrogen.

3. Results and discussion

3.1. Performances of the two bioreactors

The performances of the two bioreactors are shown in Fig. 3(a) and (b). The effluent COD and TP concentrations in the ICS-SBBR were slightly greater than those of the TCS-SBBR under the same loading rate. When the C/N ratios were 10.0, 5.0 and 3.3, the ICS-SBBR removed up to 87.2%, 92.3% and 97.7% of COD at an average influent COD concentration of 332 mg/L and the TCS-SBBR removed 85.2%, 91.1% and 94.3%. The TP removal efficiencies of the ICS-SBBR and TCS-SBBR at an average influent TP concentration of 5.26 mg/L and the same C/N ratios reached up to 95.0%, 97.0% and 97.2% and 94.1%, 96.3% and 95.7%, respectively. There was no significant difference between the ICS-SBBR and the TCS-SBBR in removing COD or TP (P > 0.05), indicating that the two SBBR systems behaved similarly in removal efficiencies of COD and TP. In addition, the COD removal efficiencies of the ICS-SBBR and TCS-SBBR increased gradually as the C/N ratios decreased from 10.0 to 3.3, which is likely due to the growth of organisms at the lower C/N ratios being substrate limited, leading to an insufficient carbon source for denitrification. This result was also reported by Xia et al. (2008), who reported the COD removal efficiency increased to 90.1%, 91.4% and 95.2% with a decrease in the C/N ratio from 3:1 to 5:1 to 10:1, and that at the ratio 3:1, the low denitrification efficiency seemed to be caused by a lack of organic carbon compounds for use as electron donors.

The TP removal was significant in both systems. This result is in agreement with the observation of Kim et al. (2008), who reported...
that phosphorus removal was not affected by an increase in initial ammonium concentration in the SBBR.

Fig. 3(c) and (d) show the nitrogen removal performances in the ICS-SBBR and TCS-SBBR. As shown in Fig. 5 (c), when the C/N ratio was 10.0, pseudo-steady states were obtained in the two bioreactors at days 7 and 5, respectively. Beyond that point, the NH$_3$–N concentrations in the effluents of both the ICS-SBBR and the TCS-SBBR were almost 0 mg/L and the average removal efficiencies reached 94.4% and 93.0%, respectively. Similarly, when the C/N ratio was 5.0, the NH$_3$–N concentrations in the effluents of the ICS-SBBR and the TCS-SBBR were also very low, and the average removal efficiencies reached 98.7% and 98.6%, respectively. However, when the C/N ratio decreased to 3.3, the average NH$_3$–N concentrations in the effluents of the ICS-SBBR and the TCS-SBBR increased dramatically to 18.34 and 20.11 mg/L, respectively. Furthermore, the average NH$_3$–N removal efficiency of the ICS-SBBR decreased to 80.0%, slightly higher than that of the TCS-SBBR (78.1%). The decrease in average NH$_3$–N removal efficiency was probably due to a deficit in carbon source for the growth of organisms. The NH$_3$–N removal efficiency was not significantly different between the ICS-SBBR and TCS-SBBR at three nitrogen-loading rates (Fig. 4).

As shown in Fig. 3(d), the TN removal was significantly influenced by nitrogen loading rate. Better nitrogen removal was achieved at higher C/N ratios. TN removal efficiencies of 87.8% and 81.0% in the ICS-SBBR and 87.7% and 65.4% in the TCS-SBBR were obtained at C/N ratios of 10.0 and 5.0, respectively. Ge et al. (2010) demonstrated that nitrogen removal had a positive correlation with influent COD/TN in a pilot-scale modified step feed process. Xia et al. (2008) found the removal of total nitrogen reached the highest efficiency of 78.4% at a C/N ratio of 5 when investigating the nitrogen removal performance in a compact suspended carrier biofilm reactor. However, Munch et al. (1996) reported that C/N ratios of 11.1 and 11.2 were the optimal values for an SBR system, leading to the best removals of both nitrogen and organic carbon, in agreement with the observations in the current study.

Additionally, although the effect of operation strategy on NH$_3$–N removal was not obvious, the removal of TN differed between the two systems (Fig. 3(d)). The TN removal efficiencies in the ICS-SBBR reached 87.8%, 81.0% and 58.3% at C/N ratios of 10.0, 5.0 and 3.3, which were higher than those in TCS-SBBR (87.7%, 65.4% and 46.1%) particularly when the C/N ratio was 5.0 and 3.3, indicating that the ICS-SBBR was more effective for TN removal. Therefore, there was overall significant difference in removing TN between the ICS-SBBR and the TCS-SBBR (P < 0.05). The significant difference in the TN removal efficiencies indicates that the ICS-SBBR behaved differently in nitrogen removal at C/N ratios of 5.0 and 3.3. This may be because the cyclical, alternating aerobic-anoxic operation of the ICS-SBBR resulted in a longer overall anoxic phase, and that the denitrification in the ICS-SBBR proceeded further than in the TCS-SBBR. Nevertheless, the aeration time of the ICS-SBBR was shorter during one operational cycle due to its special operation mode, and the ICS-SBBR biofilm was thicker (1.20–2.10 mm) than in the TCS-SBBR (0.90–1.50 mm) (Table 1). Accordingly, the SND efficiency of the ICS-SBBR was higher than of the TCS-SBBR. Gieseke et al. (2002) found that oxygen was initially limited to a penetration depth of 200–250 μm, and even at an aeration of 3 h penetration of oxygen occurred only up to a depth of 1.5 mm, in agreement with the conclusion of this study. Therefore, in present experiment, the thicknesses of biofilm could be penetrated partially. In addition, as shown in Fig. 4(a), phosphate release did not occur in the anoxic phase of the ICS-SBBR, which might be associated with denitrifying phosphorus removal using nitrate as an electron acceptor. However, this phenomenon was not found in the TCS-SBBR. Therefore, the TN removal efficiencies in the ICS-SBBR were 15.6% and 12.2% at C/N ratios of 5.0 and 3.3, respectively, much higher than in the TCS-SBBR. This

![Fig. 3. Performances of ICS and TCS at different C/N ratio: (a) COD. (b) TP. (c) NH$_3$–N. (d) TN.](image-url)
observation came up to the expectation derived from the investigations of other researchers (Kim et al., 2008; Xia et al., 2008).

3.2. Characteristics of ICS-SBBR and TCS-SBBR in a total operation cycle

The total operation cycle of the ICS-SBBR is shown in Fig. 2. In the typical operation cycle, water samples were obtained at the point when the aerobic phase and anoxic phase alternated. In the TCS-SBBR, water samples were taken every hour and the systems were operated for 12 h.

3.2.1. Variation of COD concentration in the total operation cycle

The variations in COD concentrations during the total operation cycle of the ICS-SBBR and TCS-SBBR are shown in Figs. 4(a) and (b), respectively.

After an initial 30 min aeration, the COD concentration decreased sharply from 309.5 to 31.74 mg/L in the ICS-SBBR, due to the initial adsorption and aerobic degradation. Chiou and Yang (2008) also demonstrated that COD was removed by physical adsorption and biological transformation. The adsorbed carbon could be stored in the biofilm, and subsequently served as a carbon source for phosphorus uptake and denitrification. After the following 30 min non-aeration phase, the COD concentration was reduced to 23.81 mg/L. Then, as shown in Fig. 4(a), the COD concentration increased slightly to 31.74 mg/L after the aeration phase (30 min) in the first reaction period, demonstrating that the COD reduction during the initial 30 min was mainly through initial adsorption. Thereafter, the COD concentration in the ICS-SBBR remained stable, with the degradation of COD completed in 180 min.

![Fig. 4. Variations of C, N, P in the total operation cycle in ICS, (a) ICS, (b) TCS.](image)

![Fig. 5. The variation of DO, pH, (a) ICS-SBBR, (b) TCS-SBBR.](image)

<table>
<thead>
<tr>
<th>System</th>
<th>Depth(mm)</th>
<th>0</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICS-SBBR</td>
<td></td>
<td>1.20 ± 0.02 mm</td>
<td>2.1 ± 0.01 mm</td>
<td>1.8 ± 0.01 mm</td>
</tr>
<tr>
<td>TCS-SBBR</td>
<td></td>
<td>0.9 ± 0.01 mm</td>
<td>1.5 ± 0.02 mm</td>
<td>1.2 ± 0.02 mm</td>
</tr>
</tbody>
</table>

Table 1
Thickness of biofilm at different depth.
During the anaerobic phase of the TCS-SBBR, after 30 min, the COD concentration decreased sharply from 309.5 to 30.28 mg/L. Strong adsorption was also considered to be the main reason for the COD reduction (Dulekgurgen et al., 2003). As shown in Fig. 4(b), the degradation of COD required 300 min in the TCS-SBBR.

The main COD uptake activity in both SBBRs occurred during the initial 30 min, as demonstrated by other researchers (Chiou and Yang, 2008; Wang et al., 2009b). In addition, Zhang et al. (2009) showed that investigating SND via nitrite in a sequencing batch biofilm reactor that the COD decreased rapidly during the first 60 min, mainly due to adsorption of starch, and the carbon was possibly stored in deep biofilm layers.

3.2.2. Variation of $P$ concentration in the total operation cycle

As shown in Figs. 4(a) and (b), the variation in TP concentration in the ICS-SBBR was significantly different from that in the TCS-SBBR. The TP removal behavior in the ICS-SBBR and TCS-SBBR during the aerobic phase was similar to the conventional enhanced biological phosphorus removal system (EBPR), which was biologically activated treatment of a sludge system used for phosphorus removal. (Dulekgurgen et al., 2003; Hollender et al., 2002; Kampas et al., 2009). In conventional EBPR, during the anaerobic phase, poly-phosphate accumulating organisms (PAOs) take up volatile fatty acids (VFAs) in wastewater and store them to form intracellular carbon and energy substrate-polyhydroxyalkanoates (PHAs). The PAOs cleave intracellular polyphosphate to generate energy for substrate uptake and, as a result, release phosphorus. During the aerobic phase, PAOs can utilize intracellular PHAs as carbon and energy sources to enable normal metabolism and generate energy to be used for phosphorus uptake and synthesis of poly-phosphate (Blackall et al., 2002; Mullan et al., 2006; Tanwar et al., 2008). Thereby, excessive phosphorus uptake is achieved and phosphorus is removed from the liquid phase. Moreover, the anaerobic phase is widely considered to be a key stage in EBPR, because the energy required for phosphorus uptake in the subsequent aerobic phase can be ensured by a high level of PHA accumulation in the anaerobic phase (Mulkerrins et al., 2004; Zheng et al., 2009). However, in the ICS-SBBR, the phosphorus was markedly removed without phosphorus release during the anaerobic phase (Fig. 4(a)).

During the first 30 min of the calculating period (aerobic), the TP concentration decreased significantly from 5.16 to 3.26 mg/L, probably because the PAOs took up phosphorus under aerobic conditions. However, during the subsequent 30 min (anaerobic), instead of increasing, the TP concentration continued to decrease, which differs from the conventional EBPR behavior. Recently, a number of researchers (Chiou and Yang, 2008; Wachtmeister et al., 1997; Zou et al., 2006) reported that denitrifying phosphate-accumulating organisms (DPAOs) could utilize nitrate instead of oxygen as an electron acceptor for phosphorus uptake. This may be the correct explanation for the phenomena in this study. The TP concentration in ICS-SBBR decreased to 0 mg/L after 240 min (Fig. 4(a)).

In the TCS-SBBR, phosphate release under anaerobic conditions and phosphate uptake under aerobic conditions was significant (Fig. 4(b)). During the anaerobic phase, TP concentration sharply increased from 5.16 to 12.56 mg/L, while during the aerobic phase, the TP concentration dramatically decreased from 12.56 to 0 mg/L. The characteristics of TP removal corresponded with the theory of conventional EBPR (Chiou and Yang, 2008).

3.2.3. Variation of $N$ concentration during the total operation cycle

Variations of different forms of nitrogen during the total operation cycle of ICS-SBBR are exhibited in Fig. 4(a). The NH$_3$-N concentration decreased gradually over the whole cycle and the decrease was more significant during the aerobic phase than the anoxic phase. This phenomenon was due to the high DO concentration acting as an electron acceptor during the aerobic phase in the ICS-SBBR. The NH$_3$-N concentration was reduced to the minimum (0.27 mg/L) after 420 min. However, TN concentrations declined slowly during the calculating period and accelerated during the reaction periods. When the reaction time reached 420 min, the TN concentration decreased to the minimum (10.58 mg/L).

In the TCS-SBBR, NH$_3$-N and TN concentrations decreased slowly during the anaerobic phase (Fig. 4(b)) and then sharply decreased during the first 60 min of the aerobic phase. Throughout the whole cycle, NH$_3$-N and TN concentrations decreased to their lowest values (NH$_3$-N: 0 mg/L; TN: 18.00 mg/L) at reaction times of 540 and 600 min, respectively. In addition, although the minimum NH$_3$-N concentration in the TCS-SBBR was lower than that in the ICS-SBBR, the TN removal efficiency in the ICS-SBBR was much higher than that in the TCS-SBBR, demonstrating that the ICS-SBBR had attained a better denitrification than TCS-SBBR.

The NO$_3$ - N concentration increased during the aerobic phase and decreased during the anoxic phase in the TCS-SBBR. (Fig. 4(b)), which differed from that in the ICS-SBBR. During the operation of the ICS-SBBR, the DO concentration was not less than 0.5 mg/L even in the anoxic phase. During the aerobic phase, although the DO concentration in the reactor was maintained at 6–8 mg/L (Fig. 5(a)), oxygen partially penetrated the biofilm, generating an oxygen gradient (Gieseke et al., 2002). Nitrifiers existed in the external biofilm at high DO concentration, while the denitrifiers were preferentially active in the internal biofilm at low DO concentrations. Therefore, SND occurred in the bio reactor. The NO$_3$ - N concentration increased gradually from 0.05 to 5.40 mg/L and then decreased slowly to 0.01 mg/L in the ICS-SBBR. The peak NO$_3$ - N concentration (5.40 mg/L) was higher than that reported elsewhere (about 0 mg/L) (Kim et al., 2008), indicating shortcut nitrification–denitrification via nitrite occurred in the ICS-SBBR (Zhang et al., 2009).

In the TCS-SBBR, there was a slight amount of NO$_3$ - N and NO$_2$ - N produced during the anaerobic phase and the NO$_3$ - N concentration increased gradually and remained constant at 600 min during the aerobic phase. Additionally, NO$_3$ - N concentrations increased gradually from 0.05 to 10.40 mg/L and then decreased to 0 mg/L during the same phase. The peak NO$_3$ - N concentration was 10.40 mg/L, higher than that in the ICS-SBBR, demonstrating that SND via nitrite in the TCS-SBBR was stronger than that in the ICS-SBBR. In the ICS-SBBR and TCS-SBBR, the $E_{\text{SND}}$ values were 93.2% and 81.7% respectively.

3.2.4. Variation of pH and DO during the total operation cycle

In ICS-SBBR, the pH and DO concentration in the typical operation cycle showed evidently regular changes reaction period (Fig. 5(a)). The highest pH was 7.60 and the lowest was 6.68. The pH displayed a regular change because nitrification consumed the alkalinity, while denitrification increased alkalinity (Ge et al., 2010). Furthermore, according to the pH curve, there was no obvious inflection point contributing to on-line control. This result was in agreement with the observation of Surampalli et al. (1997), who observed that optimal nitrification occurred between pH 7.5 and 9.0. The DO concentration increased gradually during aerobic phases and when the DO concentration reached about 7.0 mg/L, the pollutants were removed to a minimum.

Compared with the ICS-SBBR, significant differences in the variations of pH and DO concentration were observed in the TCS-SBBR during the whole operation cycle (Fig. 5(b)). In the aerobic phase, the pH decreased from 7.10 to 6.43, and increased from 6.43 to about 7.45 in the aerobic phase. During the aerobic phase, the DO concentration remained at 0 mg/L but during the aerobic phase, the DO concentration increased gradually over 180–360 min. There was a plateau in the DO concentration when the reaction time of
the total operation cycle was 360–420 min, showing that the nitrification was complete, and the DO concentration then increased progressively to 6.88 mg/L. It was clearly observed that the overall DO concentration in the ICS-SBBR was higher than that in the TCS-SBBR during the aerobic phase, because the DO concentration consumption was lower.

3.3. Economic analysis

Based on the above analysis, when the C/N ratio was 5.0 (COD = 309.50 mg/L, TN = 63.61 mg/L, TP = 5.16 mg/L), 180, 240, 420 and 420 min were needed to achieve the best COD, TN, NH₄–N and TP removals, respectively, in the ICS-SBBR. To obtain the best overall performance, the optimal ICS-SBBR reaction time was defined as 420 min. In contrast, the best removals were at 300, 360, 540 and 600 min in the TCS-SBBR, and similarly, the optimal reaction time for the TCS-SBBR was 600 min. According to this, the aeration time of the optimal reaction cycles in the ICS-SBBR and TCS-SBBR were calculated as 263 and 420 min, respectively. Clearly, the ICS-SBBR saved about 40% energy and 30% hydraulic retention time (HRT) compared with the TCS-SBBR under the same aeration flow rate, indicating that the SBBR could be operated and maintained economically by using an ICS-SBBR. The savings in time and energy for complete phosphorus and nitrogen removal would increase the efficiency of the ICS-SBBR and provide a further competitive edge, compared to conventional systems. In addition, the HRT could be efficiently shortened and the exploitation of the reactor volume enhanced.

4. Conclusions

The ICS-SBBR could run in an alternating aerobic-anoxic environment in a single time-oriented bioreactor and achieve a remarkable performance. Three different C/N ratios (10.0, 5.0 and 3.3) were used to compare the performances of the ICS-SBBR and the TCS-SBBR. At these C/N ratios, the average COD removal efficiencies reached 87.7%, 92.3% and 97.6%, and the average TP removal efficiencies were 97.6%, 95.0% and 97.0% in the ICS-SBBR. In the typical operation cycle, the reaction and aeration times in the ICS-SBBR were shortened by 180 and 157 min, respectively, compared with the TCS-SBBR.

Acknowledgements

This project was jointly supported by Water Pollution Control and Treatment Key Projects (2009ZX07102-002-01) and the Key Science and Technology Program (No. 108027) of Ministry of Education of the People’s Republic of China.