Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.839396

52 (2014) 4895–4903
July

Taylor & Francis
Taylor & Francis Group

Enhanced nitrogen removal and energy saving of intermittent aeration-modified oxidation ditch process

Bo-Lin Li[a,b,c,*], Zhi Zhang[c,d], Ye Li[a,b], Meng-Ting Song[a,b], Chi Zhang[c,d]

[a]*School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan 430070, China Tel. +86 13886099366; email: bolly1221@163.com*
[b]*Key Laboratory of Hubei Province for Mineral Resources Processing and Environment, Wuhan 430070, China*
[c]*Faculty of Urban Construction and Environmental Engineering, Chongqing University, Chongqing 400045, China*
[d]*Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing 400045, China*

Received 3 March 2013; Accepted 21 August 2013

ABSTRACT

To enhance the removal effect of nitrogen from municipal wastewater and to reduce the operating energy consumption of an oxidation ditch, a modified carrousel oxidation ditch, which established the selection zone, the anaerobic zone, and the anoxic zone, was chosen for study. In addition, the nitrification rate, denitrification rate, and effluent quality were chosen as feasibility criteria, and the operating conditions of intermittent aeration were optimized in a pilot-scale experiment and studied during productive debugging. The results showed that intermittent aeration can enhance the nitrogen removal effect and reduce energy consumption. The characteristic feature of the internal reflux of the modified carrousel oxidation ditch without power consumption was fully utilized, the flow rate in the main reaction zone became large, and the internal reflux flow was increased by enlarging the opening of the internal reflux valve appropriately during the aeration stage. In addition, the pre-anoxic zone was used for nitrogen removal. In the stop aeration stage, the flow rate in the main reaction zone became smaller and the internal reflux flow decreased. The main reaction zone and the anoxic zone together were used for nitrogen removal. In the operating conditions in which there is 1 h of aeration and 2 h of non-aeration, the internal reflux ratio was 195–235% in the aeration stage compared with 55–105% in the non-aeration stage. The effluent COD and NH_4^+-N can meet the discharge standard consistently. Compared with the continuous aeration condition, the effluent total nitrogen in the intermittent aeration condition decreased from 16–27.6 to 9–15 mg/L, the average removal rate increased from 50.5 to 72.8%, and the average power consumption decreased by 30.9%.

Keywords: Carrousel oxidation ditch; Intermittent aeration; Nitrification rate; Denitrification rate; Nitrogen removal

1. Introduction

The carousel oxidation ditch, which originated in the Netherlands, is a simple and efficient wastewater treatment process that is widely used all over the world. Globally, it has become a preferred municipal sewage treatment process [1,2]. The latest improvement in the carrousel oxidation ditch process is mainly reflected in the addition of a selection zone, an

*Corresponding author.

anaerobic zone, and an anoxic zone before the main reaction zone of the traditional oxidation ditch, which further enhances the nitrogen and phosphorus removal capacity of the process and prevents sludge expansion [3,4]. Rotary brushes, aeration wheels, and other surface aerators have been used to supply oxygen to the carrousel oxidation ditch, resulting in low oxygen transmission efficiency and significant energy consumption [5,6]. In addition, the oxidation ditch generally uses extended aeration technology, which exhibits low biochemical efficiency and often leads to excessive aeration during operation. This not only increases operating costs, but also increases the amount of dissolved oxygen carried into the anoxic zone by internal reflux. Since this can lead to disturbance to the nitrogen removal environment of the anoxic zone, the removal rate of total nitrogen (TN) was reduced, and the effluent TN easily exceeded the discharge standard.

Some scholars have studied the continuous influent and effluent process, which has intermittent aeration, and they generally believed that, compared with the continuous aeration process, the intermittent aeration process can achieve a better nitrogen removal effect and low-energy consumption. The intermittent aeration process in a traditional activated sludge system was studied, and the results showed that when the aerobic time accounts for 40–50% of the oxygen cycle time, the system can obtain the largest extent of nitrogen removal [7]. The effluent TN concentration could be reduced to 8 mg/L or less by reducing the aeration rate of the alternating anoxic and aerobic reactor from 0.33 to 0.23 in an alternating aerobic–anoxic system, which was set up to treat domestic sewage [8]. When the ratio of aeration time and non-aeration time was 1, the intermittent aeration oxidation ditch system could obtain the best nitrogen removal effect [9]. Anoxic zones that occur in the oxidation ditch because of aeration and agitation would help improve the denitrification effect [10,11]. There are engineering examples of an intermittent aeration oxidation ditch process, such as the Nitrox^{TM} process [12]. In this traditional oxidation ditch process (with no pre-anoxic zone), influent NH_4^+ is limited to not more than 30 mg/L in order to avoid decrease in the level of nitrogen removal.

By regulating the aeration mode, an anoxic–aerobic alternating state was formed in the oxidation ditch along the flow direction. Thus, the efficiency of removal of nitrogen improved. Guo Changzi et al. used an SBR reactor to mimic the intermittent aeration mode in the oxidation ditch along the flow direction (expressed as "step aeration mode" in the text) [13]. When the volume ratio between the anoxic zone and the aerobic zone was 1, the best effect of nitrogen removal was achieved [the TN removal rate was 66%]. Periodic aeration promoted denitrification, and simultaneous nitrification and denitrification in the anoxic zone. Liu et al. rationally optimized the ratio of the aerobic zone such that the stability of the effluent from the reactor was superior to the new discharge standards for China: NH_4^+-N < 5 and TN < 15 mg/L [14].

The sludge oxygen uptake rate (SOUR) has a very good correlation with the rate that microorganisms utilized substrate and proliferation of micro-organisms [15]. In activated sludge, after the interruption of aeration at a certain time, if the SOUR of activated sludge has not been significantly reduced, the impact of stopping aeration on the activity of the sludge is not great [16]. Previous scholars have introduced the SOUR as the feasibility criterion of the intermittent aeration process. They studied the productive experiment of nitrogen and phosphorus removal in the continuous flow and intermittent aeration processes, for which the aeration tank and the sedimentation tank were jointly built. The results showed that with aeration for 3 h and non-aeration for 3 h, the nitrogen removal was enhanced in the effluent [17].

At present, many studies have focused on the traditional oxidation ditch process, while most of the new or reconstructed and expanded wastewater treatment plants (WWTPs) in the world use the modified oxidation ditch process, which establishes a pre-selection zone, an anaerobic zone, and an anoxic zone. The pollutant degradation pattern of the modified oxidation ditch system may be different from that of a traditional oxidation ditch. In addition, the extent of the impact of intermittent aeration on sludge activity has been characterized by SOUR. However, for WWTPs which need to enhance biological nitrogen removal, using the nitrification rate and the denitrification rate to characterize sludge activity will provide more direct guidance.

Based on this information, the modified carousel oxidation ditch, which establishes a selected area, an anaerobic zone, and an anoxic zone, was chosen for study, and the nitrification rate, denitrification rate, and effluent quality were chosen as feasibility criteria. The best combination of aeration time and non-aeration time in a pilot-scale experiment and the productive debugging in an actual WWTP were studied together, in order to achieve energy savings based on the effluent that can satisfy the discharge standard. In this paper, we attempted to explore the variation pattern of nitrification and denitrification rates in the intermittent aeration oxidation ditch system. Investigating the degradation of pollutants in this system will be helpful for the application of intermittent aeration technology in an oxidation ditch.

2. Materials and methods

2.1. General conditions in the oxidation ditch process

The test was carried out in Chongqing. A WWTP with a design capacity of 10,000 m^3/d was used to study the productive oxidation ditch, and a pilot-scale oxidation ditch with a design capacity of 25 m^3/d was used in this study. The productive oxidation ditch was taken as a reference for the pilot-scale oxidation ditch. The dimensions were designed according to the Froude similarity criteria, and the effective depth was optimized, while maintaining the same hydraulic retention time (HRT) as the productive oxidation ditch. A modified carrousel oxidation ditch process was used for the biochemical pool; the process was composed of a selected zone, an anaerobic zone, an anoxic zone, and the main reaction zone. The layout of the modified carousel oxidation ditch is shown in Fig. 1.

2.2. The quality of the influent and the effluent

The raw water in the experiment came from the effluent of the swirl grit chamber of the WWTP; the main water quality parameters are shown in Table 1. The influent TN contains about 60% of NH_4^+-N and 40% of organic nitrogen. The effluent NH_4^+-N concentration was very low, and effluent TN could not reach the discharge standard consistently, which indicates that the nitrification ability of the system was excessive but the denitrification ability was inadequate.

2.3. Experimental methods

The operation mode of the experiment was continuous influent and effluent with intermittent aeration. The purpose of the test was to determine a better operating condition combination of aeration time and non-aeration time of the process. The test was divided into two phases. First, the pilot-scale oxidation ditch was used to carry out the complete nitrification and denitrification test, and the longest nitrification time and denitrification time could be determined preliminarily. The multiple sets of the test were carried out in different combinations of aeration time and non-aeration time, so the better combinations could be determined according to effluent quality, nitrification rate, and denitrification rate. Then, the test to determine the better operating condition combinations was carried out to debug and verify in the productive oxidation ditch. If we compare the effluent quality and the energy consumption value before and after the debugging, the guiding recommendations for the actual operation can be proposed.

The water temperature was 22.5–25.7°C in the experimental phase, the sludge concentration was 4,500–5,500 mg/L, the sludge age was 15–20 d, and the external reflux ratio was 65–80%. The size of the reflux flow was controlled by an internal reflux valve, and it was affected by the flow rate of the mixture liquid at the location of the reflux valve (the zone between aeration wheel *D* and the mouth of the reflux). As the carbon source in the pre-anoxic zone was sufficient, the denitrification rate of the zone was high, so the opening of the reflux valve enlarged appropriately to maximize the enhanced nitrogen removal effect of the anoxic zone. According to the calculated effluent quantity and the flow rate, the

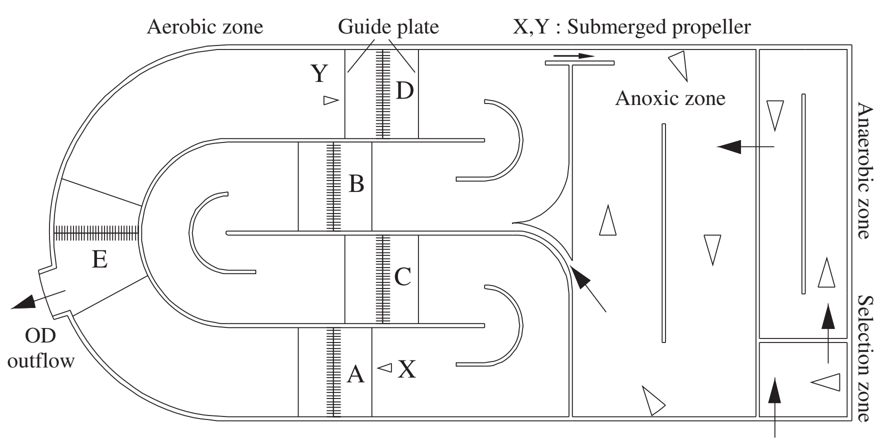

Fig. 1. Layout plan of modified carrousel oxidation ditch.

Table 1
The main raw water quality parameters

Indicators		COD (mg/L)	TN (mg/L)	NH_4^+-N (mg/L)	Organic nitrogen (mg/L)	NO_3^--N (mg/L)	NO_2^--N (mg/L)
Influent	Range	178–355	29.5–53.7	15.2–34.0	10.5–28.7	1.05–2.13	0.07–0.42
	Average value	222	42.6	26.2	18.8	1.75	0.11
Effluent	Range	10–25	15.8–26.6	0.3–1.8	–	12.61–23.45	0.02–0.95
	Average value	16	21.2	0.7	–	16.88	0.65
Discharge standard		60	20	8(15)	–	–	–

Notes: The values outside of the brackets is the control target when water temperature >12℃, the value inside of brackets is the control target when the water temperature ⩽12℃.

results showed the following: in the aeration stage, the internal reflux ratio was 195–235%; in the non-aeration stage, the internal reflux ratio was 55–105%. The influent water quantity was (0.87×10^4)–(0.96×10^4) m^3/d in the experimental phase, which was lower than the designed value (10,000 m^3/d). The actual total HRT was 13.16–14.6 h; the selected zone was 0.31–0.35 h, the anaerobic zone was 1.22–1.35 h, the anoxic zone was 3.23–3.58 h, and the main reaction zone was 8.4–9.32 h.

In addition to conventional indicators, the *re-aeration method* was used to detect the nitrification rate [18], and the denitrification rate was detected in accordance with previous scholars [19]. It was noteworthy that the denitrification rate in the aerobic phase and the nitrification rate in the anoxic phase were characterized by the sludge denitrification activity and the nitrification activity; it was not implied that denitrification occurred in the aerobic stage or that nitrification occurred in the anoxic stage.

3. Results and discussion

3.1. An optimized experiment with pilot-scale intermittent aeration operating conditions

3.1.1. The complete nitrification and denitrification test

The changes in the effluent COD, organic nitrogen, NH_4^+-N, NO_3^-, NO_2^-, and TN of the system in the reaction cycle under conditions A and B (aeration for 3 h, non-aeration for 6 h) are shown in Fig. 2; the changes in the nitrification rate and the denitrification rate of the reaction cycle are shown in Fig. 3. Under the continuous aeration condition A, the effluent COD concentration was 10–15 mg/L, with an average of 12 mg/L; thus, it can satisfy the discharge standard consistently. The effluent NH_4^+-N concentration was less than 1 mg/L and TN concentration was higher than 20 mg/L; the nitrification was excessive while the denitrification was inadequate. The nitrification rate was 21 mg NH_4^+-N/(gVSS·d), which is less than half of the designed value of the WWTP [50 mg NH_4^+-N/(gVSS·d)]; the denitrification rate in the anoxic zone was 35 mg NO_3^-/(gVSS·d), which is much lower than the designed value of the WWTP [100 mg NO_3^-/(gVSS·d)].

In the aeration stage of condition B, the organic oxidation reaction, the ammonification reaction, and the nitrification reaction occurred; the concentration of COD, organic nitrogen, and NH_4^+-N in the system decreased rapidly; and NO_3^- concentration increased gradually. The concentration of TN was decreased by denitrification in the anoxic zone, and the concentration of the indicators no longer changed after 2 h. At 1 h aeration followed by the action of the five aeration wheels, the DO concentration in the main reaction zone increased rapidly, up to 3.5–5 mg/L (an average of 4 mg/L). After aeration was stopped, the high DO concentration in the main reaction zone could not be quickly reduced, so the concentration of COD, organic nitrogen, and NH_4^+-N rose relatively slowly; some accumulated COD, organic nitrogen, and NH_4^+-N were degraded; dissolved oxygen was consumed completely with the extension of the non-aeration time; and the concentration of COD, organic nitrogen, and NH_4^+-N showed an apparent rising trend. The internal reflux ratio became smaller (55–105%) after aeration stopped, and the nitrogen removal effect of the anoxic zone could not be maintained. The unused carbon source and electron acceptor (NO_3^-) remained in the main reaction zone, creating favorable conditions for denitrification of the main reaction zone. Thus, both the main reaction zone and the anoxic zone contributed to denitrification, and the effluent NO_3^- concentration showed a declining trend until the end of the denitrification reaction. During the early stage of the non-aeration time, the quantity that NO_3^- was reduced to was

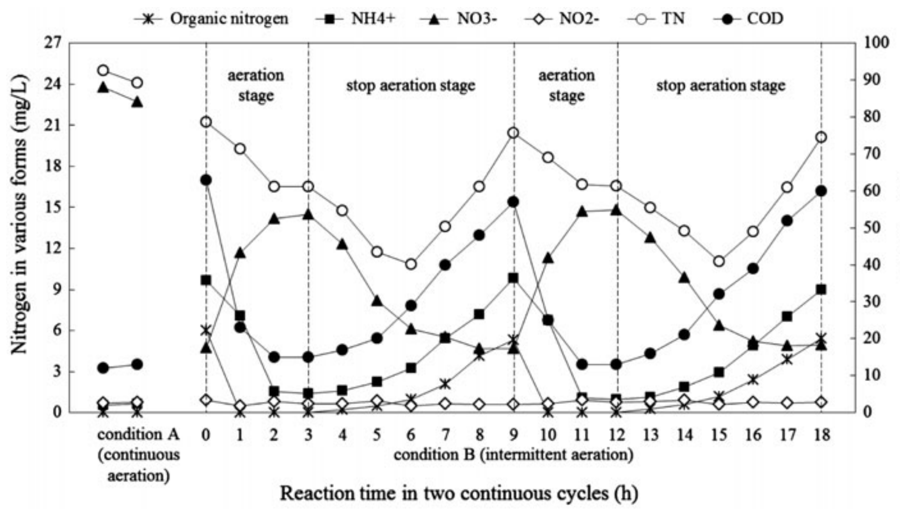

Fig. 2. The changes of effluent COD, organic nitrogen, NH_4^+, NO_3^-, NO_2^-, and TN of the system in reaction cycle under the condition A and condition B.

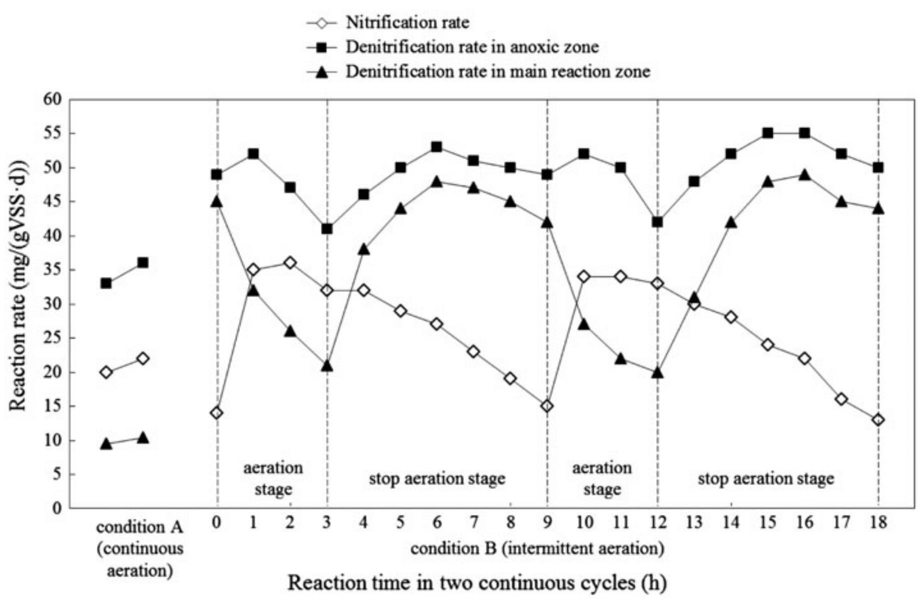

Fig. 3. The changes of nitrification rate and denitrification rate of reaction cycle under the condition A and condition B.

greater than the quantity of the accumulated NH_4^+–N and organic nitrogen; thus, the TN was reduced and fell to the lowest value. With the accumulated amount of NH_4^+-N being increased, the effluent TN concentration increased gradually.

Stopping aeration has a significant influence on the nitrification rate, which reduced from 32 mg NH_4^+-N/(gVSS·d) at the beginning to 14 mg NH_4^+-N/(gVSS·d) at the end of the non-aeration stage. Nitrifying bacteria activity was quickly restored after aeration resumed, and the nitrification rate was increased to 34 mg NH_4^+-N/(gVSS·d) 1 h after aeration. The change of the denitrification rate in the anoxic zone was relatively stable for a while, while it reduced a little in the latter part of the aeration stage. This may be due to the dissolved oxygen in the anoxic zone, which was carried back from the main reaction and gradually increased. There is a certain inhibition of the denitrification reaction of the anoxic zone. After aeration stopped, the denitrification rate could be restored. The main reaction zone experienced an alternating aerobic and anoxic state in the reaction cycle. The denitrification rate was changed by a wide margin; it decreased rapidly to 22 mg NO_3^-/(gVSS·d) after the beginning of the aeration stage, but it could be restored after aeration stopped, and it gradually increased to 49 mg NO_3^-/(gVSS·d).

Through analysis, the following conclusion can be drawn: the organic oxidation reaction and the nitrification process have already been completed after 2 h of aeration. When the non-aeration time continued for 2 h, the concentration of TN reduced to the lowest point. When the non-aeration time continued for 5 h, the concentration of NO_3^- reduced to the lowest point, and the denitrification process was completed. After a comprehensive consideration of the effluent quality and the reaction rate, the aeration time was identified as 2 h preliminarily and the longest stopping aeration time was 4 h; the next experiment will be based on these.

3.1.2. The combination of aeration and non-aeration and test methods

Considering that the longest aeration time was 2 h and the longest non-aeration time was 4 h, we avoid changing the run-time daily in order to facilitate the production management. The change unit was set to 1 h, and six combinations of aeration time and non-aeration time could be attained. The combinations were: 1–1 (aeration for 1 h, non-aeration for 1 h), 1–2, 1–3, 2–1, 2–2, and 2–4. The quality of the influent and the effluent in the reaction cycle, and the nitrification and denitrification rates of each combination, will be studied to determine the optimal combination. The sampling interval time of each operating condition is 0.5 h.

3.1.3. Analysis of test results of different combinations of operating conditions

The changes in the effluent COD, organic nitrogen, NH_4^+-N, NO_3^-, NO_2^-, and TN in the reaction cycle of aeration and non-aeration of different combinations are shown in Fig. 4. The effluent COD, NH_4^+-N of all operating conditions can meet the discharge standard (60, 8 mg/L) consistently. The operating conditions 1–1 and 2–1 bore the problem of excessive aeration, the effluent COD was less than 15 mg/L, the effluent NH_4^+-N was less than 1 mg/L, but the denitrification effect was poor. The effluent TN bore the risk of exceeding the discharge standard. The study of the anaerobic–anoxic oxidation ditch system by Peng Yongzhen et al. showed that excessive aeration would destroy the stability of denitrification and reduce the TN removal rate from 80 to 40% [4]. Operating conditions 1–3 and 2–4 had a relative lack of aeration; the effluent COD, NH_4^+-N, NO_3^-, and TN fluctuated greatly in the reaction cycle; and the effluent quality was unstable. The effect of operating conditions 1–2 and 2–2 on the effluent quality was optimal, and the effluent COD, NH_4^+-N, and TN could meet the discharge standard in the reaction cycle. The effluent of the aeration period and non-aeration period were relatively stable, with no significant fluctuations, which was conducive to the effluent discharging steadily from the secondary sedimentation tank ultimately.

The changes in the nitrification rate and the denitrification rate in the reaction cycle are shown in Fig. 5. With the extension of the non-aeration time, the nitrification rate of the three combinations whose aeration time was 1 h and the three combinations whose aeration time was 2 h, all showed an upward trend at the end of the aeration stage, which indicated that the stopping aeration may have a strengthening effect on the activity of nitrifying bacteria. The effluent NH_4^+-N concentration can be controlled at a relatively high level by controlling the amount of aeration, which can improve the nitrification rate of sludge. The nitrification reaction can be completed quickly; the amount of aeration and the operating costs can be reduced under the premise so that the effluent can meet the discharge standard [20].

Comparing the six kinds of conditions, the denitrification rate of conditions 1–1 and 2–1 in the anoxic zone was the lowest relatively, and the denitrification rate of condition 1–2 was the highest, with an average value of 72 mg NO_3^-/(gVSS·d). In the reaction cycle, the denitrification rate in the main reaction zone of all

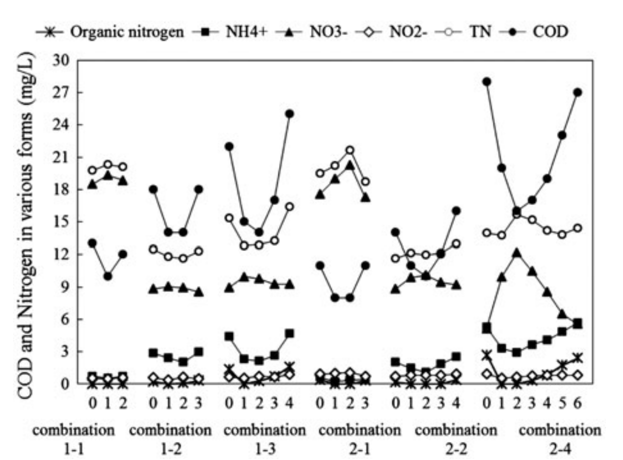

Fig. 4. The changes of effluent COD, organic nitrogen, NH_4^+, NO_3^-, NO_2^-, and TN of different combinations of aeration and stop aeration.

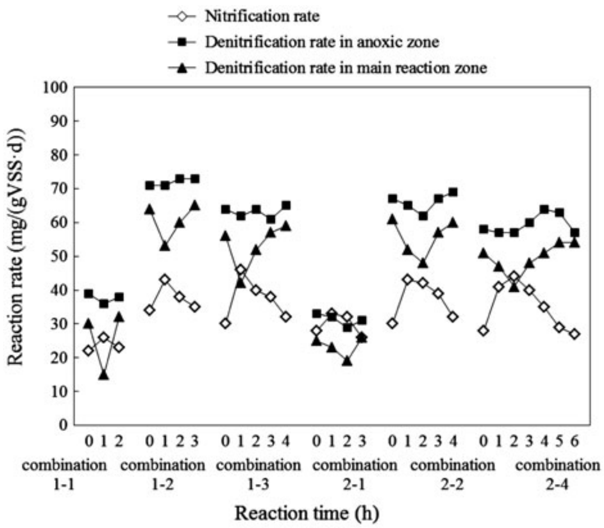

Fig. 5. The changes of nitrification rate and denitrification rate of different combinations of aeration and stop aeration.

conditions showed a trend that first decreased and then increased. At the end of the non-aeration stage, the denitrification rate in the main reaction zone reached the highest value, of which operating condition 1–2 was the highest: 65 mg NO_3^-/(gVSS·d). This was followed by condition 2–2, whose denitrification rate reached 60 mg NO_3^-/(gVSS·d); condition 1–1 was 32 mg NO_3^-/(gVSS·d), which was the lowest.

Through analysis, from the perspective that the effluent can meet the discharge standard, alternative conditions were 1–2, 1–3, 2–2, and 2–4; from the perspective of the stability of the effluent quality, operating conditions 1–2 and 2–2 were better than others; from the perspective of energy savings, the actual running time of aeration wheels per day, condition 1–2 for 8 h, condition 1–3 for 6 h, condition 2–2 for 12 h, and condition 2–4 for 8 h; from the perspective of reaction rate, condition 1–2 and 2–2 were the best, because the sludge activity was the highest. After comprehensive consideration, condition 1–2 and 2–2 were chosen for the long-term operating conditions.

3.2. The productive debugging test of intermittent aeration conditions

3.2.1. A comparison of the treatment effect before and after debugging

The operating conditions 1–2 and 2–2 were selected for the productive debugging test of the oxidation ditch in the WWTP, and they were compared with the continuous operating condition. Under the three kinds of operating conditions, COD, NH_4^+-N, and TN removal effects of the process are shown in Figs. 6–8. It can be seen in Figs. 6 and 7 that under the three operation conditions, the effluent COD and NH_4^+-N all met the discharge standard consistently. The effluent COD and NH_4^+-N concentration of the continuous aeration condition was the lowest, followed by operating condition 2–2. The effluent COD, NH_4^+-N concentration of condition 1–2 was the highest, which can reach 15–28 and 2.9–4.8 mg/L, respectively.

Fig. 8 illustrates that the effluent TN of the continuous aeration condition was 16–27.6 mg/L, which cannot meet the discharge standard consistently, and the effluent quality of the intermittent aeration condition can reach the discharge standard. Intermittent aeration has enhanced the removal efficiency of TN. The intermittent aeration technology of the test was designed to take full advantage of the benefits of the modified oxidation ditch. The pre-anoxic zone holds a sufficient carbon source, and the denitrification rate was high; thus, nitrogen removal in the pre-anoxic zone can be enhanced by enlarging the opening of the internal reflux valve appropriately and maintaining a high-internal reflux ratio. Xin Zhou et al. found that proper increment of the internal circulation volume of the improved Orbal oxidation ditch would improve the efficiency of nitrogen removal from the outer channel (At recycle ratio of 9.4). However, if the inner circulation volume was too large, it would dilute the carbon source, and thereby making conditions unfavorable for denitrification in the outer channel [21]. In addition, the exogenous denitrification and endogenous denitrification in the main reaction zone in an anoxic condition were used to enhance overall nitrogen removal. At the aeration stage, the flow rate in the main reaction zone became large, the internal reflux flow increased, and the pre-anoxic zone was mainly used for nitrogen removal; at the non-aeration stage, the flow rate in the main reaction zone

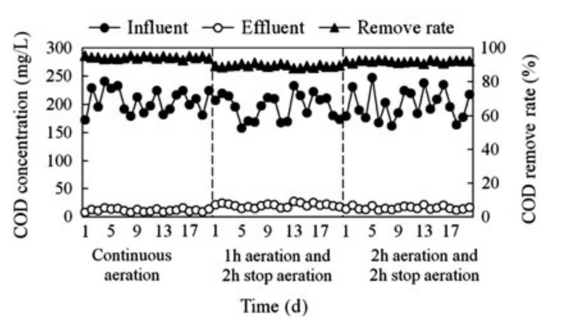

Fig. 6. The comparison of COD removal effect of the continuous operating condition and the intermittent aeration condition.

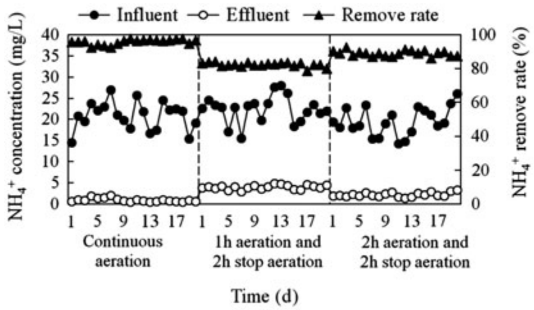

Fig. 7. The comparison of NH_4^+ removal effect of the continuous operating condition and the intermittent aeration condition.

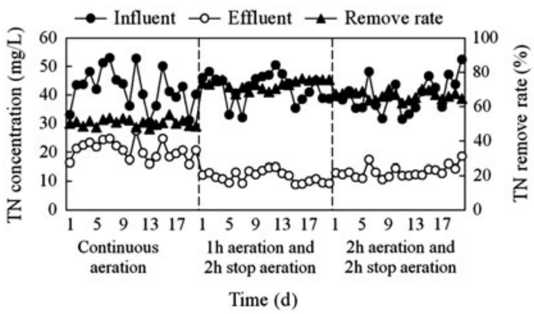

Fig. 8. The comparison of TN removal effect of the continuous operating condition and the intermittent aeration condition.

decreased and the internal reflux flow reduced; the pre-anoxic zone and the main reaction zone contributed to nitrogen removal. It can be seen that the modified oxidation ditch system can achieve efficient nitrogen removal in a single reaction cycle, so that it can maintain a low concentration of effluent TN.

Compared with the two kinds of intermittent aeration operating conditions, the effluent TN of condition 1–2 was 9–15 mg/L; thus, the nitrogen removal was slightly greater than that achieved in condition 2–2 (effluent TN was 10.8–18.6 mg/L).

3.2.2. *Comparison of aeration time and energy consumption before and after debugging*

The comparison of aeration time and power consumption of the three conditions before and after debugging of the WWTP is shown in Figs. 9 and 10. These figures illustrate that the operating power consumption of continuous aeration operation was 0.286–0.330 kW h/m^3, an average of 0.307 kW h/m^3; the operating power consumption of the condition in which aeration time was 1 h and non-aeration time was 2 h was 0.193–0.228 kW h/m^3, an average of

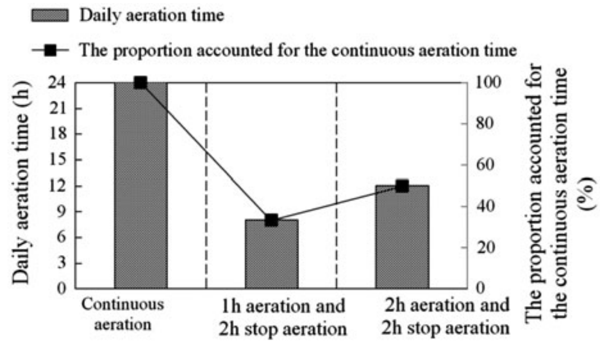

Fig. 9. The comparison of aeration time of continuous aeration and intermittent aeration.

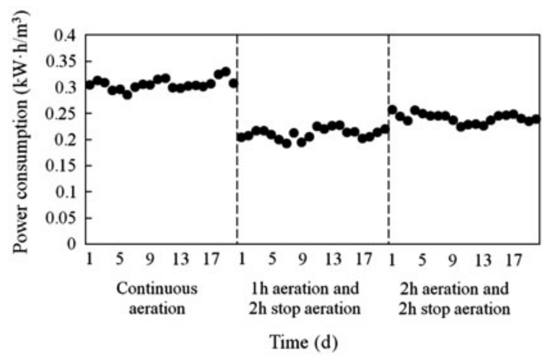

Fig. 10. The comparison of operating power consumption of continuous aeration and intermittent aeration.

0.212 kW h/m^3; the electricity consumption was decreased by 30.9% compared to the continuous aeration operating condition before debugging; the operating power consumption of the condition with aeration for 2 h and non–aeration for 2 h was 0.225–0.258 kW h/m^3, an average of 0.242 kW h/m^3, for which the electricity consumption was decreased by 21.2%. Compared with the two kinds of intermittent aeration operating conditions, the wheels of the operating condition 1–2 ran 8 h per day, which was lower than 12 h of the operating condition 2–2; the aeration time of condition 2–2 accounted for 33.3% of the aeration time of the continuous aeration condition, Therefore, condition 2–2 achieved the lowest power consumption.

4. Conclusions

Although the removal rate of NH_4^+-N under the continuous aeration operation of the modified carousel oxidation ditch was high, excessive aeration led to excessive oxidation of the sludge, which was not conducive to denitrification and caused high-energy consumption. Intermittent aeration technology has been used to transform the process, through the study of pilot-scale experiments and productive debugging tests; that the following conclusions can be drawn.

The maximum aeration time was 2 h and the longest non-aeration time was 4 h; these times were determined by the complete nitrification reaction and denitrification reaction in a pilot-scale test. The nitrification rate was 35 mg NH_4^+-N/(gVSS·d) when the aeration time was 2 h, the denitrification rate of the anoxic zone was 53 mg NO_3^-/(gVSS·d) when the non-aeration time was 4 h, and the denitrification rate was 48 mg NO_3^-/(gVSS·d) in the main reaction zone.

Under the operation condition with aeration for 1 h and non–aeration for 2 h, the internal reflux ratio was 195–235% during aeration, while it was 55–105% when aeration stopped. The effluent COD, NH_4^+-N can meet the discharge standard consistently; compared with the continuous aeration condition, the effluent TN of the WWTP of the intermittent aeration condition was reduced from 16–27.6 to 9–15 mg/L, and the average removal rate was increased from 50.5 to 72.8%. The process has achieved greater extent of nitrogen removal since the effluent can meet the discharge standard consistently, and the average power consumption was decreased by 30.9%.

Acknowledgments

Financial support was provided by Water Pollution Control and Management of Major Special Science and Technology of China (Grant no. 2012ZX07104-002) and the Fundamental Research Funds for the Central Universities (Grant no. 2013-IV-081, Grant no. 2013-ZY-074, and Grant no. 2012-YB-17).

References

[1] S.B. Thakre, L.B. Bhuyar, S.J. Deshmukh, Oxidation ditch process using curved blade rotor as aerator, Int. J. Environ. Sci. Technol. 6 (2009) 113–122.
[2] A. Yerachmiel, Single sludge nitrogen removal in an oxidation ditch, Water Res. 18 (1984) 1493–1500.
[3] H.X. Hou, S.Y. Wang, Y.Z. Peng, Z.G. Yuan, F.F. Yin, G. Wang, Anoxic phosphorus removal in a pilot scale anaerobic-anoxic oxidation ditch process, Front. Environ. Sci. Eng. China 3 (2009) 106–111.
[4] Y.Z. Peng, H.X. Hou, S.Y. Wang, Y.W. Cui, Z.G. Yuan, Nitrogen and phosphorus removal in pilot-scale anaerobic-anoxic oxidation ditch system, J. Environ. Sci. China 20 (2008) 398–403.
[5] B.A. Saida, H. Latifa, C. Hayet, Aeration management in an oxidation ditch, Desalination 252 (2010) 172–178.
[6] A. Abusam, K.J. Keesman, K. Meinema, G.V. Straten, Oxygen transfer rate estimation in oxidation ditches from clean water measurements, Water Res. 35 (2001) 2058–2064.
[7] A. Dey, D.D. Truax, B.S. Magbanua, Optimization of operating parameters of intermittent aeration-type activated sludge process for nitrogen removal: A simulation-based approach, Water Environ. Res. 83 (2011) 636–642.
[8] K. Hyunook, J.H. Oliver, PH and oxidation-reduction potential control strategy for optimization of nitrogen removal in an alternating aerobic-anoxic system, Water Sci. Technol. 73 (2001) 95–102.
[9] S. Furukawa, K. Tokimori, J. Hirotsuji, New operational support system for high nitrogen removal in oxidation ditch process, Water Sci. Technol. 37 (1998) 63–68.
[10] X.D. Hao, H.J. Doddema, Use of contact tank to enhance denitrification in oxidation ditches, Water Sci. Technol. 34 (1996) 195–202.
[11] X.D. Hao, H.J. Doddema, Simultaneous nitrification and denitrification in a pasveer oxidation ditch, Bioresour. Technol. 59 (1997) 207–215.
[12] Metcalf, Eddy, Inc., Wastewater Engineer Treatment and Reuse, 4th ed., McGraw-Hill Education, New York, 2003.
[13] C.Z. Guo, W. Fu, X.M. Chen, D.C. Peng, P.K. Jin, Nitrogen-removal performance and community structure of nitrifying bacteria under different aeration modes in an oxidation ditch, Water Res. 47 (2013) 3845–3853.
[14] Y.C. Liu, H.C. Shi, Z.Q. Wang, L. Fan, H.M. Shi, Approach to enhancing nitrogen removal performance with fluctuation of influent in an oxidation ditch system, Chem. Eng. J. 219 (2013) 520–526.
[15] H. Spanjers, G. Olsson, P.L. Dold, Respirometry in control of the activated sludge process, Water Sci. Technol. 34 (1996) 117–126.
[16] M.R. Neiva, J.L.A. Galdino, P.F.C. Catunda, A.V. Haandel, Reduction of operation costs by planned interruption of aeration in activated sludge plants, Water Sci. Technol. 33 (1996) 17–27.
[17] X. Gao, T.R. Long, Research on oxygen uptake rate of continuous inflow-intermittent aeration process, Water Wastewater Eng. 28 (2002) 4–8, (in Chinese).
[18] W. Chen, D. Wu, N.W. Zhu, X.Y. Zheng, J. Li, P.C. Yang, Enhanced ammonia removal and nitrification rate of A/A/O-MBR combined process, J. Civ. Architectural Environ. Eng. 32 (2010) 90–95, (in Chinese).
[19] S.P. Wang, Q.Q. Wang, L.L. Hui, S.Y. Jin, The determination of denitrification rate of step-feed A/O nitrogen removal process, Environ. Eng. 26 (2008) 56–58, (in Chinese).
[20] H.X. Hou, H.C. Shi, Y.Z. Wang, G. Wang, R.H. Xie, Study on energy saving and nitrogen and phosphorus removal of intermittent aeration oxidation ditch process, Water Wastewater Eng. 35 (2009) 34–38, (in Chinese).
[21] X. Zhou, Y.P. Han, X.S. Guo, Enhanced total nitrogen removal performance in a modified Orbal oxidation ditch system with internal nitrate recycle, Chem. Eng. J. 228 (2013) 124–131.