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RESEARCH ARTICLE

Flow characteristic and wastewater treatment performance of a pilot-scale airlift oxidation ditch

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Abstract A pilot-scale airlift oxidation ditch using bubble diffuser and baffle as aerator was operated in a wastewater treatment plant (WWTP) to investigate its flow characteristic and wastewater treatment performance. Compared with the conventional oxidation ditch process, effective depth and oxygen utilization efficiency of this new process was improved by underwater aeration. Furthermore, it had a reversed velocity distribution, which decreased from the bottom to the top on vertical section. Velocity measurement showed that a velocity over 0.2 m/s at the bottom was sufficient to prevent sludge settlement during long term operation. Application of these concepts would save land area and energy consumption by about 25%–50% and 55%, respectively. In this new system, organic biodegradation and nitrification could be well achieved. Denitrification could occur steadily in the straight part by adjusting the airflow rate. An average TN removal rate of 63% was achieved with dissolved oxygen (DO) concentrations between 0.6 mg/L and 1.5 mg/L. The main pollutants in the effluent could meet the strictest discharge standard (COD < 50 mg/L, NH_4^+–N < 5 mg/L, and TN < 15 mg/L) in China now.

Keywords airlift oxidation ditch, flow characteristic, wastewater treatment

1 Introduction

The oxidation ditch, originally developed by Passveer in 1953, was designed as a simplified method for the treatment of small quantities of sewage at low capital and operating costs. With the development of new aerators, such as vertical rotor and draft-tube, oxidation ditches became widely used at large-scale wastewater treatment plants. Consequently, oxidation ditches has become a significant wastewater treatment technique in the world [1, 2]. The main advantage of oxidation ditch is the ability to achieve pollutant removal objectives with low operational requirements, operation and maintenance costs. However, it requires a larger land area than other activated sludge processes [3]. This limits the feasibility of oxidation ditches in urban, suburban, or other areas, where land acquisition costs are relatively high.

Due to the substantial increase of domestic and industrial wastewater discharges, there rises an urgent demand of wastewater treatment plants in China. For example, the Taihu basin district, which covers only 3% area of China but contributes 20% to the national economy, over 150 new wastewater treatment plants (WWTPs) will be built from 2010 to 2020. With the development of wastewater treatment technology in China, land cost and energy consumption have become crucial factors in choosing suitable processes for WWTP construction. Considering this challenge in China, a novel process with both the advantages of conventional oxidation ditches and less cost should be developed to treat municipal wastewater.

Airlift reactor is mainly used in biological processes and can also be useful in wastewater treatment [4–6]. In an airlift reactor, the air flow transfers oxygen for the biomass and induces a global circulation of solid particles. In our study, airlift technology is transplanted to airlift oxidation ditch (AOD) by using bubble diffusers and baffles [7]. Compared with the conventional oxidation ditches using mechanical aeration devices, both the effective depth and oxygen utilization efficiency of AOD could be improved by underwater aeration. Thus, the new process has the advantage of lower land costs and energy consumption. Based on the experimental results of a lab-scale AOD, a pilot-scale AOD was designed and operated for nine months in a WWTP near the Taihu basin. The main aim of the pilot research was to investigate the flow characteristic and wastewater treatment performance of AOD.

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2 Experimental

2.1 AOD system

Figure 1 shows the general format of AOD. The pilot AOD is made of steel and has a volume of 54 m^3. Its maximum treatment capacity is 216 m^3/d. In AOD, surface aeration devices were replaced by bubble diffusers and baffles. The riser and downcomer were composed of three steel baffles. Rubber air diffusers were installed at the bottom of each riser. A roots blower supplied air to the diffusers, which transferred oxygen and drove flow at the same time. The dissolved oxygen (DO) concentration could be easily adjusted by changing the airflow rate. The influent was pumped from the mixing tank of the WWTP to the inlet of AOD. The effluent flowed from the outlet to a clarifier. After sedimentation, the effluent was discharged to the anoxic tank of the WWTP and the sludge returned to the inlet of the ditch.

2.2 Velocity measurement

Figure 2 illustrates the planform and dimension of AOD, in which coordinate z presents the depth of the ditch. The AOD was divided into 13 parts, including the riser, the downcomer, the straight part, and the curving part. A rotor velocimeter (LGY-Ⅲ, Nanjing Hydraulic Research Institute, China) was used to measure the velocity in the different parts of AOD. The experiment was first carried out with clean water in order to investigate the flow pattern in single channel. Afterward, velocity was measured in wastewater with activated sludge to find out the minimum flow velocity that could prevent sludge settlement at the bottom.

2.3 Wastewater treatment

The raw water concentrations were very low due to the surface water permeation and combined sewer system. During the research period, the sewer system adjacent to the WWTP was upgraded, which made the industrial water in the raw water increase from 15% to 40%. Considering these nonideal and complex conditions, methanol (CH_3OH) and ammonium bicarbonate (NH_4HCO_3) were added into the raw water as influent. The concentrations of the main pollutants are described in Table 1.

Table 1 Concentrations of the main pollutants

pollutants	raw water/($mg \cdot L^{-1}$)	influent/($mg \cdot L^{-1}$)
COD	91–210	181–325
NH_4^+–N	10.2–21.9	23.6–45.1
TN	16.1–26.1	28.8–48
TP	0.6–3.6	0.6–3.6

During the first two months after start-up, the AOD system was operated under various hydraulic retention times (HRT) for carbonaceous organic and ammonia nitrogen removal. After that, the influence of DO

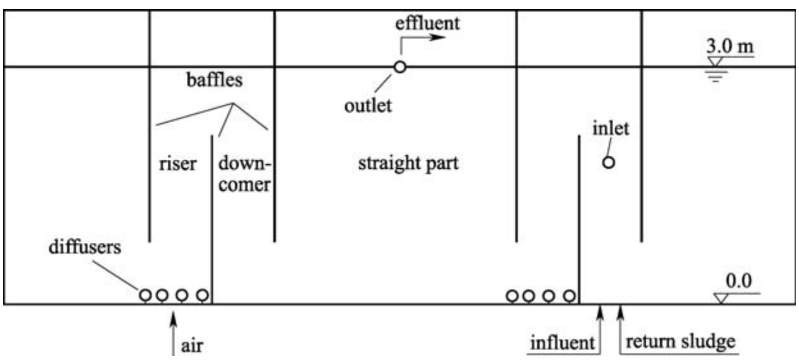

Fig. 1 General format of AOD

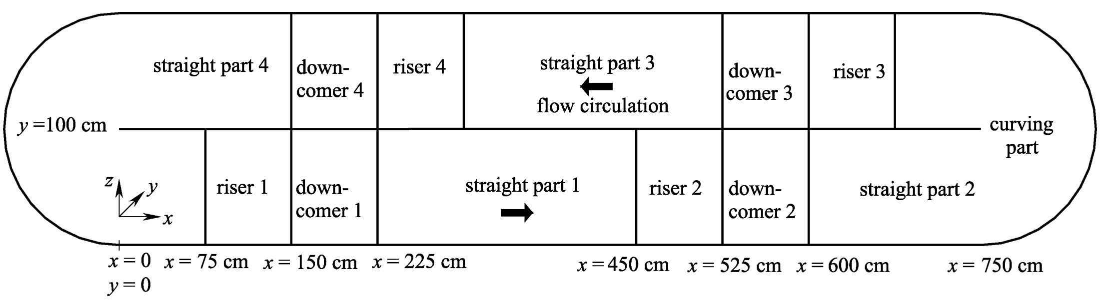

Fig. 2 Planform and dimension of AOD

concentration on total nitrogen (TN) removal was investigated. The main purpose was to obtain the process parameters that could satisfy the current discharge standard in Taihu Basin, which is the strictest local standard in China because of the heavy environmental burden. Table 2 shows the discharge standard of most concerned pollutants in Taihu Basin [8].

Table 2 Discharge standard of main pollutants for WWTP in Taihu Basin

Nr.	type	COD /($mg \cdot L^{-1}$)	NH_4^+–N /($mg \cdot L^{-1}$)	TN /($mg \cdot L^{-1}$)	TP /($mg \cdot L^{-1}$)
1	WWTP I	50	5(8*)	20	0.5
2	WWTP II	60	5(8*)	15	0.5

Notes: WWTP I: Ratio of industrial wastewater is less than 50%; WWTP II: Ratio of industrial wastewater is between 50% and 80%; *: Temperature is lower than 12°C.

The influent and effluent samples were taken from the influent pipe and the effluent from the outlet of the clarifier separately. Chemical oxygen demand (COD), ammonia nitrogen (NH_4^+–N), total nitrogen (TN), and total phosphorus (TP) were analyzed according to Standard Methods [9]. MLSS and temperature were measured by an online instrument (Optiquant SST, HACH Company, USA). DO was measured by a dissolved oxygen meter (YSI DO200, YSI Incorporated Company, USA).

3 Results and discussion

3.1 Flow pattern in a single channel

Figure 3 describes the flow pattern at the plane of $y = 50$ cm, which is the center section in a single channel, and the straight lines present the baffles. Liquid velocity in x and z directions were measured on 44 points in the ditch. As shown in Fig. 3 (air flow rate is 170 m^3/h), water flow had the maximum velocity in the riser because of the aeration. The stream began to move downward when it reached the top of the middle baffle and changed its direction again under the last baffle in the downcomer. In the straight part, water flow with relative higher velocity at the bottom caused circumfluence and turbulence in the top. Then, water flowed to the next riser and circulated in the reactor. The velocity profile along the depth direction was reversal to the conventional oxidation ditch with surface aeration. Therefore, it is necessary to have a precise understanding of velocity distribution in the straight part.

3.2 Velocity distribution in the straight part

Figure 4 plots the velocity magnitude of different heights in straight part 1 (see Fig. 2). The horizontal velocity (v_x) dropped considerably with the increase of the depth. The average v_x at the bottom ($z = 25$ cm) was 0.25 m/s and decreased to only 0.03–0.05 m/s in the middle and top area ($z = 50$ cm and 250 cm). It was worth noting that the bottom was the driving area of the straight part. To explain

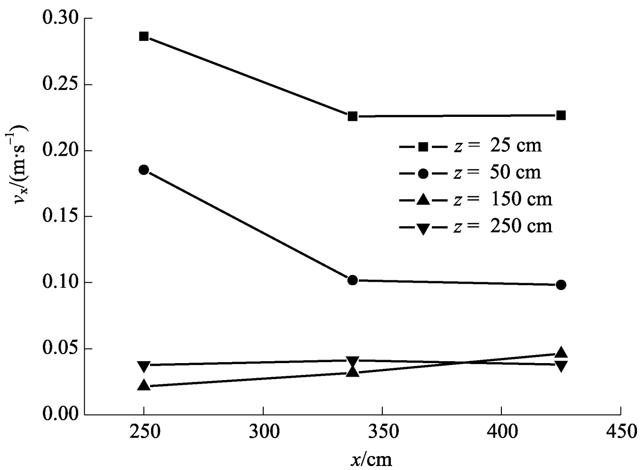

Fig. 4 Velocity distribution in the straight part

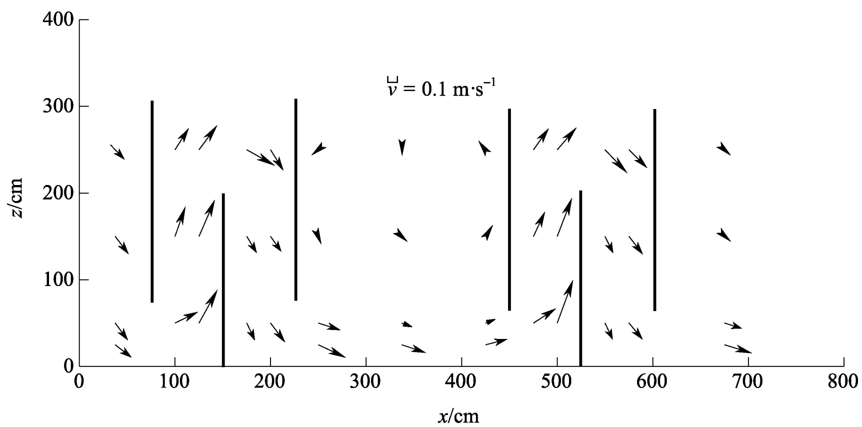

Fig. 3 Vector diagram of liquid velocity in a single channel

it briefly, the straight part could be considered as two large layers, the bottom layer and the upper layer. The height of the last baffle ($z = 75$ cm) was the boundary of the two layers. The bottom layer drove the top layer to flow by the viscous force between them. Application of this concept could effectively prevent settling of activated sludge at the bottom. However, it was unsure whether such low velocities in the top could keep the sludge in suspension and make a complete mixture. Consequently, experiments with wastewater were carried out, in which both the velocity and MLSS were measured.

3.3 Minimum velocity preventing sludge settlement

For a conventional oxidation ditch with horizontal rotors, the surface velocity is higher, and the velocity in the ditch decreases with the approach to the bottom. A velocity of more than 0.25 m/s is recommended for a conventional oxidation ditch to maintain the solids in suspension [3]. The most important reason for this is that velocities less than 0.25 m/s will cause sludge settlement and interfere with the biological treatment. However, the minimum velocity could probably be the maximum in AOD for the reversed flow pattern.

During the first week of sludge cultivation, horizontal velocity (v_x) and MLSS were measured in the middle of the straight part 1 ($x = 337.5$ cm). According to the experimental results of the influence of airflow rate on velocities [10], airflow rate (Q_{air}) decreased from 40 to 20 m^3/h. As described in Fig. 5, the maximum velocity at the bottom ($z = 5$ cm) was only 0.07 m/s at $Q_{air} = 20$ m^3/h. MLSS in the top ($z \geqslant 225$ cm) increased from 1.55 to 1.7 g/L, which meant that sludge slightly accumulate there. When Q_{air} increased to 30 m^3/h, v_x at the bottom was 0.15 m/s, and sludge accumulation in the top was reduced. When Q_{air} reached 40 m^3/h, v_x ($z = 5$ cm) was in accordance with the necessary speed for a conventional oxidation ditch. MLSS in different heights were almost the same, which indicated a good mixing in the straight part. It was also found that a velocity of 0.05 m/s in the upper layer was sufficient to keep sludge in suspension. This feature could absolutely save power input for mixing and circulation. However, it was uncertain whether such lower velocity would have a negative effect on wastewater treatment.

After treating wastewater for a long term, horizontal velocity and MLSS in the ditch were measured again. MLSS was well-balanced in the whole ditch. The main pollutants in the effluent could steadily meet the discharge standard, even if the average v_x was only 0.04 m/s in the straight part ($z \geqslant 150$ cm). Due to the impact of influent and returned sludge, v_x at $z = 5$ cm increased to 0.19 m/s with a Q_{air} of 30 m^3/h. Therefore, a velocity of more than 0.2 m/s at the bottom was recommended for the operation of the pilot-scale AOD.

3.4 Effect of HRT on contaminants removal

The removal efficiency (R) of main pollutants with different HRT was presented in Table 3. The COD removal efficiency decreased with decreasing HRT from 8.5 to 6.0 h. It was clearly indicated that the effluent COD at low HRT of 6.0 h could not meet the discharge standard. It was possible to achieve a COD effluent concentration less than 50 mg/L at the maximum loading rate of 0.88 $kg/(m^3 \cdot d)$. NH_4^+–N effluent exceeded the discharge standard with HRTs of 7.5 h and 6.0 h, but the reason was not the increased loading rate. When HRT was 7.5 h, the temperature in the ditch was lower than 13°C due to the heavy snow. The low temperature declined the nitrification rate. In a period of 6 h of HRT, the sewer system was under upgrading and wastewater from chemical industries entered the system. The activity of nitrifying bacteria was severely inhabited by wastewater with high concentration phenol. Although the temperature increased to 15°C, the NH_4^+–N removal efficiency still decreased to only 42.9%.

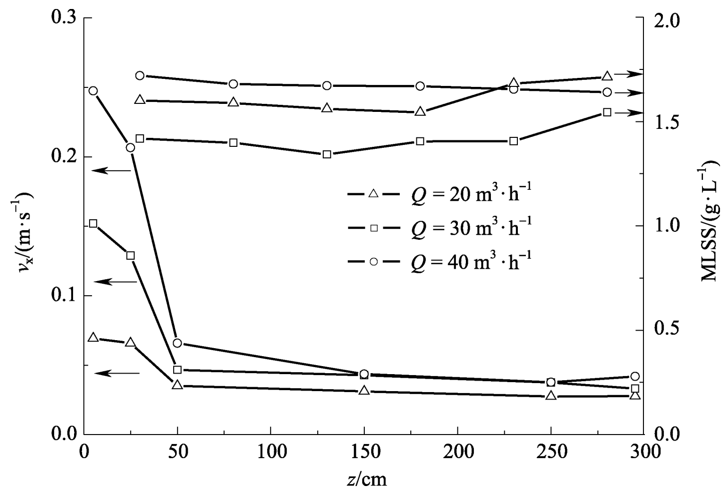

Fig. 5 Velocity and MLSS distribution with different air flow rate in the straight part

Table 3 Removal efficiency of main pollutants with different HRT

HRT	COD/(mg·L^{-1})			NH_4^+–N/(mg·L^{-1})			TN/(mg·L^{-1})			TP/(mg·L^{-1})		
	inf.	eff.	*R*/%	inf.	eff.	*R*/%	inf.	eff.	*R*/%	inf.	eff.	*R*/%
8.5	239.3	42.7	82.2	15.8	0.35	97.7	18.8	11.7	36.4	0.61	0.11	82.0
7.5	240.9	46.8	80.6	24.1	7.34	71.1	31.0	19.3	36.5	1.08	0.44	60.2
6.0	277.8	65.8	76.3	24.4	13.7	42.9	32.9	22.7	32.6	1.65	0.98	40.6

Simultaneous nitrification and denitrification could occur in a single channel oxidation ditch at the average DO concentrations between 0.1 and 0.5 mg/L [11–15]. Although DO concentration was over 2 mg/L during the whole operation period, the system still had a TN removal rate over 30%. It indicated that denitrification might occur in local part, and the system still had a potential to improve nitrogen removal. Phosphorus concentration was very low in the influent, and it could be removed easily by adding chemicals; therefore, the removal of TP was not investigated for further study.

3.5 NH_4^+–N removal

After upgrading the sewer system, the pilot AOD was restarted to testify its real removal capacity of NH_4^+–N and TN. The change of NH_4^+–N concentrations in both influent and effluent are shown in Fig. 6. NH_4^+–N in the effluent was stably lower than 5 mg/L, but occasionally, it was higher than 10 mg/L because of the impulsion of toxic industrial wastewater. The system had a good buffering ability and recovered by itself after about one week. Without the impact of toxic wastewater, the NH_4^+–N effluent could be lower than 5 mg/L with a loading rate less than 0.15 kg/(m^3·d).

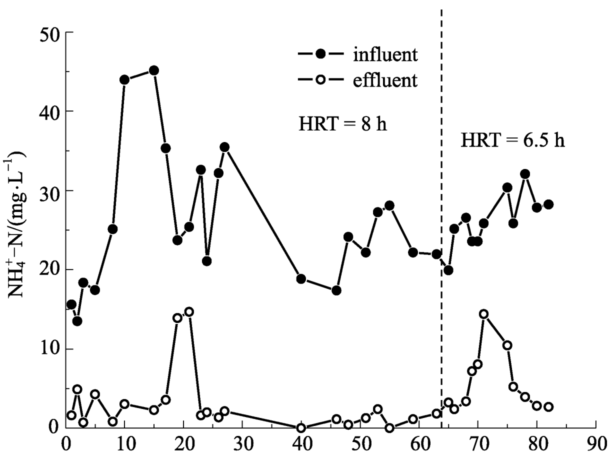

Fig. 6 NH_4^+–N concentration in the influent and effluent

3.6 TN removal

Denitrification by an oxidation ditch was easily achieved with a set of anoxic zones in the ditch. In AOD, the DO concentration reduced as the water flowed from the riser to the straight part. There existed a DO gradient about of 1–2 mg/L. An anoxic zone could be easily formed in the straight part by adjusting the airflow rate and organic load. Figure 7 shows the TN concentrations in both influent and effluent and DO in the straight part. In order to ensure the oxygen supply for nitrification, DO concentration was maintained over 2 mg/L in the first six weeks. The experimental results showed that denitrification occurred, whereas it was not stable and complete. The TN removal rate changed, ranging from 30% to 50%, and the effluent TN was higher than 15 mg/L.

Airflow rate was reduced from 40 to 30 m^3/h at the 41st day to achieve lower DO concentration between 0.6–1.5 mg/L. After HRT decreased to 6.5 h, TN concentration in the effluent was less than 15 mg/L and kept steadily for over two weeks. An average TN removal rate of 63% was obtained. The average TN concentrations in the influent and effluent were 30.7 and 11.3 mg/L, respectively. The lowest DO in the ditch was not below 0.5 mg/L, which meant that no macroanoxic zone existed in the ditch during the study. Under the circumstance, denitrification should be ascribed to microanoxic layers in flocs [16–19]. In AOD, liquid velocity in the straight part ($z > 50$ cm) was only 0.04 m/s, which could reduce both the oxygen transfer rate and turbulence intensity [20,21]. The weak turbulence was also helpful for the sludge to form large flocs and limit oxygen diffusion. Therefore, it is possible to create a microanoxic zone inside the sludge flocs although the DO outside was higher than 0.5 mg/L. This feature can effectively solve the contradiction of DO demand for nitrification and denitrification.

3.7 Land cost and energy consumption

With the same volume loading rate, the land area of oxidation ditch is only decided by the depth. The maximum depth of conventional oxidation ditches in China is usually 3.0–4.5 m. According to the aeration devices, the effective depth of AOD can reach 6.0 m. Thus, AOD can save 25%–50% land area compared with the conventional oxidation ditch.

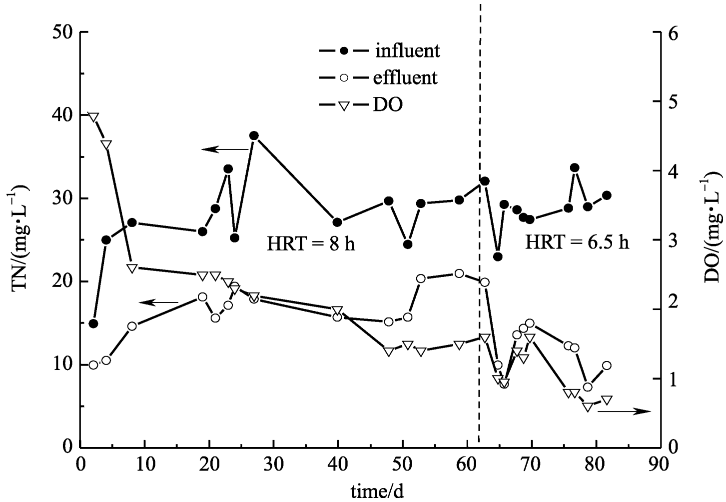

Fig. 7 Influence of DO concentration on TN removal

In oxidation ditches, the driving force required for water flow can be calculated by the following equation:

$$T = \frac{1}{2}\rho k A v^2, \tag{1}$$

where ρ is the liquid density, kg/m^3; k is the local and total drag coefficient; A is the hydraulic area of the channel, m^2; and v is the average flow velocity in the channel, m/s.

According to Eq. (1), the power input is proportional to v^2 if the energy efficiencies are equal. In a conventional oxidation ditch, the average flow velocity in the channel is approximately 0.3 m/s [22]. In this study, the average velocity of the whole channel is only 0.2 m/s with an airflow rate of 30 m^3/h. Hence, the new type of airlift oxidation ditch may save energy consumption by 55% compared with the traditional oxidation ditches.

4 Conclusions

The flow characteristic and wastewater treatment performance of a pilot-scale airlift oxidation ditch were investigated in this research. The main conclusions can be summarized as follows:

1) The airlift oxidation ditch has a reversed distribution on vertical section compared with conventional oxidation ditches. Liquid velocity decreased from the bottom to the top in the straight part, and a velocity over 0.2 m/s at the bottom was sufficient to prevent sludge sedimentation. The average velocity in the top ($z > 50$ cm) was only 0.04 m/s. However, such lower velocity did not affect the mixing and biological treatment.

2) The new process was capable of effectively removing COD, NH_4^+–N, and TN at 6.5–8.5 h of HRT. To meet the strictest discharge standard in China, the maximum loading rate of COD and NH_4^+–N was 0.88 kg/(m^3·d) and 0.15 kg/(m^3·d), respectively. A microanoxic zone could be formed in the straight part by adjusting airflow rate and HRT. Denitrification occurred steadily and an average TN removal rate of 63% was achieved with a DO concentration of 0.6–1.5 mg/L.

3) Compared with conventional oxidation ditches, both the effective depth and oxygen utilization efficiency of AOD were improved by underwater aeration. The lower velocity required for flow and mixing can also reduce the power input. Therefore, the AOD system can save land area and energy consumption by 25%–50% and 55%, respectively, compared with conventional oxidation ditches.

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