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Research Article

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Study on the Balance of Oxygen in Supply and Demand in Wastewater Treatment Plant

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Abstract
In order to accurately evaluate the comprehensive operation efficiency of aerobic biological treatment system in wastewater treatment plants (WWTPs), the process state aeration performance tester and the specific oxygen uptake rate online monitoring device were used to measure the oxygenation performance and the activated sludge performance in aeration tank, and the comprehensive operation efficiency of aerobic tank was evaluated by combining physical-chemical indexes and water quality analysis of the treatment system. The results showed that the oxygen transfer efficiency (OTE) of aerators under process state are reduced by 13.07% and 14.48% respectively compared with that in clean water in the No.3-tank and No.6-tank, and the aeration uniformity index (IAU) is 4.86 and 1.46 respectively. The oxygen uptake rate (OUR) in the third corridor decreased significantly, but dissolved oxygen (DO) was a high level. Oxygen in supply (Qs) was much greater than oxygen in demand (Cs), which have resulted a large waste of energy consumption. Finally, the subsection regulation strategy was proposed based on the principle of oxygen balance. The results of this study will not only help the WWTP to achieve energy-saving and consumption-reducing, but also stable operation.

Keywords: WWTP,Oxygenation Performance, Activated Sludge Performance, Oxygen Transfer Efficiency, Oxygen Uptake Rate, Oxygen Balance

Introduction

With the deepening of water pollution control in China, the wastewater treatment industry has developed rapidly. At present, the activated sludge process is still widely used in wastewater treatment plants (WWTPs) in urban China [1, 2]. The biological treatment system is the core unit of the WWTP, it is responsible for the removal of major pollutants, but it also the unit with the largest energy consumption [3]. The aeration unit accounts for 50% to 70% of the total energy consumption of the entire WWTP[4, 5]. Therefore, ensuring the stable and efficient operation of the aeration system is not only the premise for the aerobic biological treatment unit to achieve fine operation effect, but also the demand for energy-saving and consumption-reducing of the WWTP.

At present, most WWTPs have not realize accurate aeration control and fine operation, that is, the oxygen balance [6,7]. In order to ensure that the effluent can meet the discharge standar, the dissolved oxygen (DO) is generally maintained at a high level in the aerobic zone, while it can be generally controlled at 1~3 mg/Lto meet the requirements of nitrogen and phosphorus removal [8]. Among them, the oxygenation performance of aerators and the activity of activated sludge are important monitoring indicators, which represent the oxygen in supply and demand of WWTPs. Aerators are one of the most critical equipment in WWTPs, and fine-bubble diffusers are commonly used. The fine-bubble diffuser has a high oxygen transfer rate (OTR) and oxygen transfer efficiency (OTE), but it also has disadvantages such as large resistance loss and easy clogging [9, 10]. Under long-term operation, the fine-bubble diffusers will easy to be blocked by the pollutants from wastewater and activated sludge. The oxygen mass transfer efficiency will be reduced, which not only increasing the energy consumption of providing the same amount of oxygen, but also resulting in low comprehensive efficiency of the biological treatment system, unstable processing effect, and huge energy waste. The comprehensive efficiency of aerobic biological treatment system is essentially determined by the efficiency of oxygen in supply and demand [11]. The capacity of the oxygen in supply is mainly characterized by the OTE of aerators, and the efficiency of the oxygen in demand is mainly characterized by the oxygen uptake rate (OUR) (or specific oxygen uptake rate (SOUR)) of the microorganism. These two indicators directly related to the stable operation and energy consumption of the WWTP. Therefore, it is necessary to study the oxygenation efficiency and activated sludge performance based on the principle of oxygen balance.

In this study, the aeration performance indexes of aerators, activated sludge performance indexes and physicochemical indexes were measured and evaluated in the No.3-tank and No.6-tank of the Zhuyuan wastewater treatment plant (ZY-WWTP). By testing the oxygenation performance of the aeration system and the activity of activated sludge under the actual operation conditions, the regulation strategy based on oxygen balance was proposed. The basic data can be provided for the upgrading and efficiency improvement of the WWTP, which is conducive to accurately evaluating the comprehensive efficiency of the biological treatment system and optimizing the operation parameters.

Materials and Methods

Activated Sludge Systems

Field experiments were performed in the ZY-WWTP in Shanghai (China) during spring sessions. The design scale of the ZY-WWTP is 1.7 million m3/d, which adopts Anoxic Oxic (AO) process. The basic design parameters are as follows: sludge retention time (SRT) is 15 d, mixed liquor suspended solids (MLSS) is 3500 mg/L, and hydraulic retention times (HRTs) of anoxic tank and aerobic tank are 4.01 and 9.65 h, respectively.

Fig. 1 shows the schematic diagram of the wastewater treatment unit and test points (express with). The effective dimension of a single aerobic tank is: 85 m (L)×38.4 m(W)×10 m(H). The high-density polyethylene tubular fine-bubble diffusers (EKOTON AKPV-1.0, Ukrainian) were used in the aerobic tanks, the technical and specification parameters are as follows: dynamic efficiency of oxygenation (Ep) is 7.12 ($kgO_2/(kW•h)$), ventilation volume is 5~45 ($m^3/(m•h)$), single service area is 1~5 m^2, oxygen transfer efficiency (OTE) in clear water is 40%.

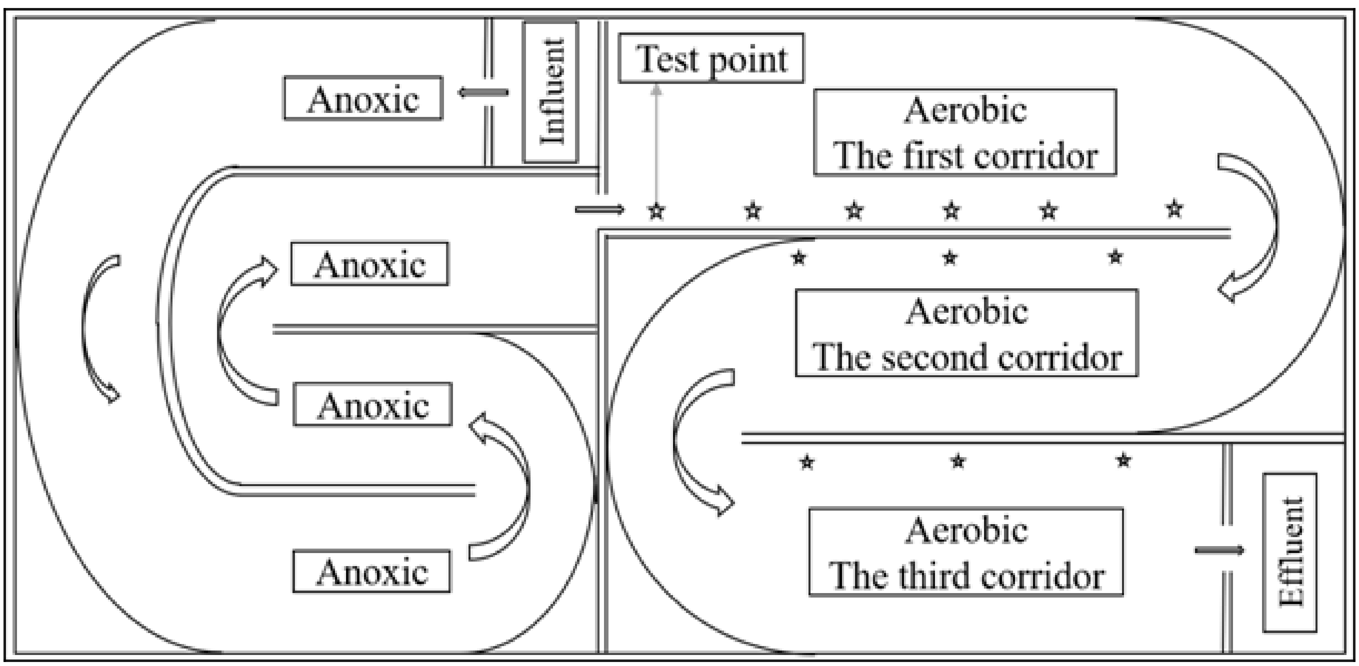

Figure 1: The Diagram of Biological Treatment Unit

The influent Quality Indexes in ZY-WWTP are shown in Table 1.

Table 1: Influent Quality of ZY-WWTP

Parameters	Range/ (mg/L)	Mean/ (mg/L)
Chemical Oxygen Demand (COD_{Cr})	114~374	232
Ammonia Nitrogen (NH_3-N)	12.1~27.2	19.9
Total Nitrogen (TN)	17.5~39.1	29.5
Total Phosphorus (TP)	3.0~7.4	4.8
pH	6.53~7.55	7.31
Wastewater temperature (°C)	17.3~19.1	18.6

Field experiments

The field experiments include two main parts: tests of the oxygenation performance of aerators and the activity of the activated sludge.

(1) Off-Gas Measurement

The OTE is an important parameter to reflect the oxygenation performance and actual operating efficiency of the aeration system [12]. It was expressed as the volumetric oxygen transfer coefficient per unit volume of power consumption under aeration conditions [13]. In this study, the oxygen transfer efficiency (OTE) and aeration capacity (Qc) of aerators in the No.3-tank and No.6-tank were measured by using the process state aeration performance tester independently developed by our team, so as to obtain the accurately actual oxygen supply value of the aerobic tank. The process state aeration performance tester is composed of aeration efficiency analyzer, gas-collecting system and other main components. The basic parameters of this device are: the measurement range of OTE is 0~60% and Qc is 0~30 m3/h, and the measurement accuracy is ±0.2% FS. Moreover, the gas-collecting hood (Zhuoyuan Hongda, Beijing) is round with a diameter of 1.73 m. The basic principle of the process state aeration performance tester is that the off-gas is collected to the gas-collecting hood through the off-gas pipe and is connected to the equipment. A small amount of off-gas is pumped into the gas analyzer through the analysis side flow pipe by the micro vacuum pump to analyze the relevant gas content in the off-gas, and the OTE under the process state is obtained by calculation [14]. The OTE is calculated by the mass balance of oxygen between ambient air and off-gas [15-17].

$$OTE=(O_2^{in}-O_2^{out})/(O_2^{in})\times 100\% \qquad \text{(Formula 2-1)}$$

Where O2 is the mole fraction of oxygen in the off-gas, %. O_2^{in} is the oxygen content in the inlet, O_2^{out} is the oxygen content in the off-gas.

Aeration uniformity index (I_{AU}) is an aeration performance index, which is used to quantitatively evaluate the degree of aeration uniformity. It is related to the valve opening of aeration pipeline and the pollution degree of aerators. I_{AU} is expressed by the standard deviation of regional aeration capacity [5]. The smaller the value is, the better the aeration uniformity is.

(2) Oxygen Uptake Rate Measurement

Oxygen uptake rate (OUR) refers to the oxygen consumption of microorganisms in unit volume of mixed liquid in unit time, it is one of the best indicators to characterize the microbial activity of activated sludge [18-20]. The OUR was tested at the point along the aerobic tank using the specific oxygen uptake rate online monitoring device independently developed by our team, the basic parameters of this device are: the range of test is 0~150 mgO_2/(L•h), test accuracy is ±(2~5)% FS. The basic principle of the specific oxygen uptake rate online monitoring device is that the test command is sent to the instrument through man-machine interface. The mixture in the aeration tank is pumped into the aeration chamber by the inflow peristaltic pump and flows through the DO probe into the vent pipeline under the action of the outflow peristaltic pump. Through the reaction process in the vent pipeline, the DO data is obtained and OUR calculation is carried out. After the determination, the mixture flows back to the biochemical tank, and the determination process and the biochemical tank form a closed loop.

$$SOUR=OUR/MLVSS \qquad \text{(Formula 2-2)}$$

Where SOUR is specific oxygen uptake rate, $mgO_{2/}$(gVSS•h). OUR is oxygen uptake rate of activated sludge, mgO_2/(L•h). MLVSS is the mixed liquor volatile suspended solids, mg/L.

Experimental Methods

(1) Measurement of performance evaluation indexes

Taking the intake of aerobic tank as the reference point, the distances from the intake of aerobic tank are 3, 12, 27, 42, 57, 77, 97, 127, 157, 187, 215 and 245 m, which corresponding to the No.1 test point, No.2 test point, … and No.12 test point respectively. The field tests were carried out in the No.3-tank and No.6-tank by using the process state aeration performance tester and the specific oxygen uptake rate online monitoring device. The measurement time of each group was 1 h. Three groups of parallel tests were conducted at each test point, and the weighted mean was taken finally. The setting of the point mainly considered that the concentration of pollutants at the inlet was higher end of the first corridor, and the biochemical reaction process was more violent. During the test, it is assumed that the longitudinal line of each corridor is completely mixed and uniform, and the test points are all near the corridor.

(2) Measurement of Physical-Chemical Indexes

The physical-chemical indexes (oxidation-reduction potential (ORP), pH, mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS)) in the aerobic tank can directly reflect the comprehensive state of the biological treatment system, which were measured by the WTW portable digital multi parameter measuring instrument (Multi 3420, Germany).

The 250 mL mixture samples were taken at each test point, and the supernatant was taken after centrifugation to determine the pollutant concentration. The experimental procedures for laboratory analysis were carried out according to standard methods for examination of water and wastewater, these test indexes included chemical oxygen demand (COD_{Cr}), ammoniacal-nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP) [21].

(3) Oxygen Balance Indexes

In this study, the oxygen in supply and demand was calculated based on formula 2-3 and 2-4.

$$Qs=(Q_g^{hood})/Aera^{hood} \times Aera^{tank} \quad \text{(Formula 2-3)}$$

$$Cs=OUR \times Aera^{tank} \quad \text{(Formula 2-4)}$$

Where Qs is the oxygen in supply, kg/h. Cs is the oxygen in demand, kg/h. Q_g^{hood} is the gas-collecting capacity, m3/h. $Aera^{hood}$ is the gas-collecting area of hood, m^2. $Aera^{tank}$ is the aerobic tank volume, m^3.

Results and Discussion

Evaluation of Aeration Performance of Aerators

The performance tests of aerators were carried out in the No.3-tank and No.6-tank in ZY-WWTP by using the process state aeration performance tester. As shown in Fig. 2(a), the OTE of aerobic tank ranged from 20.02% to 39.01% in the No.3-tank, with an average of 26.93%. At the first corridor, the OTE of the first two test points were as low as 20.02% and 20.10%, which were lower than the average level of the whole aerobic zone. In the middle section of the second corridor, the OTE of the No.8 test point is obviously higher than others, which have reached 39.01%, it can basically reach the OTE (40% in clear water) in the state of clear water. Overall, the average OTE of the three test points in the second corridor was 31.79%, which indicates that the performance of aerators in this test area is better than the first and third corridor. The OTE in No.9, No.10 and No.11 test points were 26.31%, 23.2% and 26.05% respectively, which were far lower than the expected value. The OTE test results showed that there are serious fouling, blockage or other circumstances of aerators in the NO.1, No.2, No.3, No.4, No.5, No.9, No.10 and No.11 test points in the No.3-tank, where the uneven aeration has led to the increase of bubbles and the decrease of OTE. Moreover, due to the decrease of pollutant concentration along the corridor, the inhibition of oxygen mass transfer (K_{La}) is reduced, and the average OTE of the second and third corridor are on the rise.

In the same way, the test results of oxygenation performance of the No.6-tank were analyzed. As shown in Fig. 2(b), the OTE of the No.6-tank with a small fluctuation compared with the No.3-tank, ranging from 19.08% to 37.5%, with an average of 25.52%. The OTE of the first and second corridor fluctuated slightly, with an average of 22.73%. However, the OTE increased rapidly in the third corridor, the OTE of the No.10, No.11 and No.12 were 28.42%, 37.5% and 35.83%, respectively. Combined with field investigation, the aeration pipeline of the No.6-tank was maintained two years ago, and there is no obvious big bubble point at present. However, according to the results of oxygenation performance test, the OTE in some aerobic aeras has dropped to a lower value, which indicate that the fouling has begun to exist.

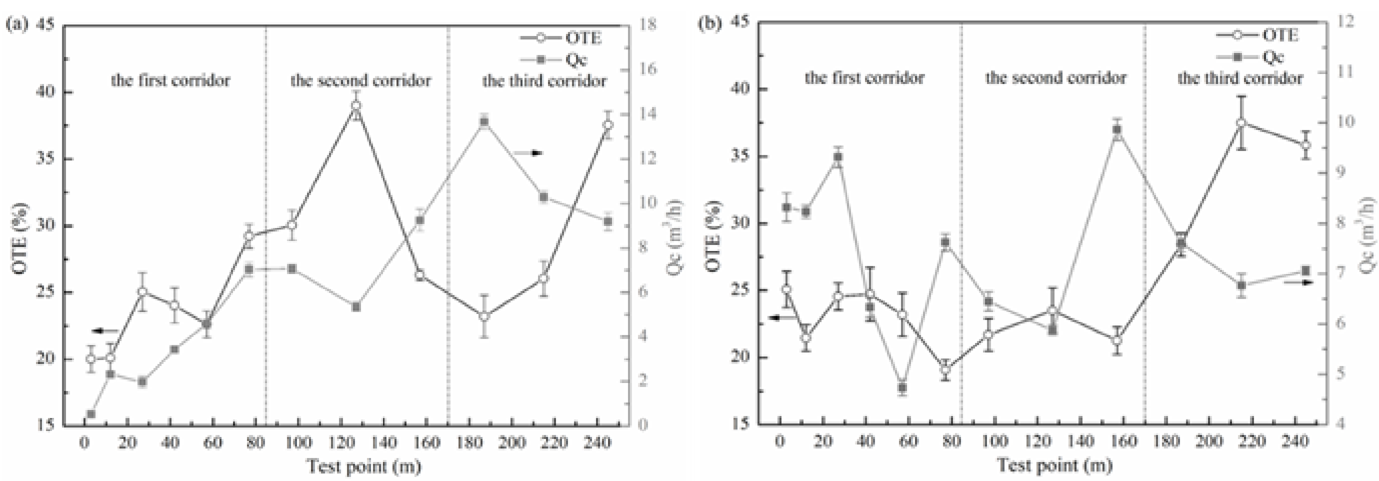

Figure 2: The Oxygenation Performance of Aerators. (a) No.3-tank and (b) No.6-tank.

Moreover, the gas-collecting capacity (Qc) at the front end of the No.3-tank is fluctuates greatly, increasing from 0.538 m3/h to 13.679 m3/h along the corridor, and the Qc in the area of gas-collecting hood (gas-collecting area: 3 m3) is only 0.583 m3/h. Which indicates that oxygenation performance of the first two test points in the front-end of aeration zone is abnormal, where the aerators are likely fouling or blocked. The regional aeration rate of the first corridor in the No.3-tank is much lower than that of the second and third corridor, the average of Qc at each test points in the first corridor is 3.318 m3/h, and the second and third corridors is 7.229 m3/h and 11.055 m3/h, respectively. While the fluctuation range of the Qc is relatively small in the No.6-tank, which is basically in the range of 4.735~9.866 m3/h. Combined with field observation, there are large bubbles on the surface of the first corridor. There are mainly two reasons, the first one is serious blockage of aerators, the second is damage of pipeline valve. From the first corridor to the second corridor, the OTE increased gradually.

By calculating the I_{AU}, it can be known that the overall I_{AU} of the No.3-tank and No.6-tank are 4.86 and 1.46 respectively, and the aeration uniformity of the No.3-tank is in a poor state. According to the field observation of the oxygenation performance in the aerobic zone, the phenomenon of “boiling” exists at many test points in the No.3-tank. The large bubble aeration on the surface of the aerobic zone indicates that the blockage or damage of the aerator in this area has been serious. Similarly, the OTE of some test points is lower than the average of the whole aerobic tank can also shows that.

Through the measurement of aeration performance, the test points with low OTE and Qc of the biological treatment system can be found accurately and sensitively, so as to guide the maintenance of the aeration system in time. According to the test results, the aerators in some aeras need to be cleaned or replaced to improve the operation efficiency. Results showed that these aerators where the No.1, No.2, No.3, No.4, No.5, No.10 in the No.3-tank, the No.6, No.7, No.9 in the No.6-tank need to be repaired or replaced.

Evaluation of the Oxygen in Demand

The performance evaluation of activated sludge in the No.3-tank and No.6-tank were shown in the Fig. 3. The OUR value in the two aerobic tanks showed a downward trend along the corridors, ranging from 39.6 $mgO_2/(L•h)$ to 19.06 $mgO_2/(L•h)$ in the No.3-tank, from 41.05 $mgO_2/(L•h)$ to 31.06 $mgO_2/(L•h)$ in the No.6-tank, respectively. The concentration of pollutants in the front of the first corridor in the No.3-tank is relatively high, and there are more available substrates for microorganisms, and their activity is relatively high. With the decrease of pollutant concentration, the oxygen demand of microorganisms also decreases, and OUR is decreasing. The OUR decreases rapidly from the No.6 test point (33.2 $mgO_2/(L•h)$) to the No.7 test point (26.14 $mgO_2/(L•h)$) of the No.3-tank. The gradual rise of DO indicates that the degradation of pollutants is completed basically. The decrease of OUR in the No.6-tank was lower, the oxygen demand of activated sludge remained at a higher level, and the last test point was within 31.06 $mgO_2/(L•h)$. According to the calculation of specific oxygen uptake rate (SOUR), the performance of activated sludge is at the middle level in the ZY-WWTP. The SOUR in the No.3-tank is in the range of 8.19~19.89 $mgO_2/(gVSS•h)$, and the activity of the activated sludge in the No.6-tank is lower than the No.3-tank, which is in the range of 10.06~15.43 $mgO_2/(gVSS•h)$. Combined with the test results of oxygenation performance and the change regulation of OUR in the No.3-tank, it can be seen that the k_{La} is obviously lower than others in the first corridor of the No.3-tank. Lower OTE and higher OUR have indicated that insufficient oxygen supply in this aeration aeras, which are likely to form an anoxic zone in the aeration tank.

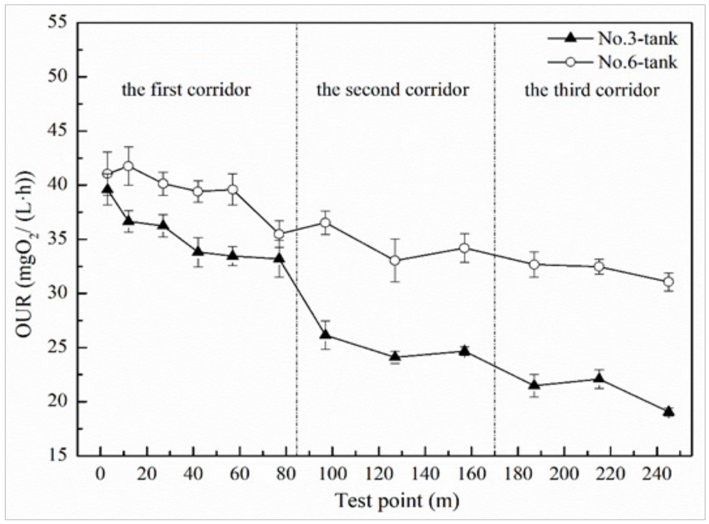

Figure 3: The change of OUR along the Aerobic Tank

The variation trend of DO in the aerobic zone of the two biological tanks are shown in Fig. 4. It can be seen from the figure that the DO concentration in the first corridor of the No.3-tank is close to 0 mg/L, which indicates that the aeration rate of the first corridor is quite low. The corridor is basically in anoxic state, which is not conducive to nitrification in aeration tank. At the beginning of the second corridor, DO concentration began to increase significantly and was approximately 0.98 mg/L in the No.9 test point. After entering the third corridor, DO concentration gradually increased to 1.48 mg/L, and was close to 2.95 mg/L at the end of the corridor. Because of the low aeration efficiency and the high activated sludge activity, the DO concentration of the front end is quite low while in the end section is higher. which leads to higher DO concentration in the reflux. The mixture will carry a lot of DO return back to the anoxic tank, so the high DO concentration at the end of the aerobic tank will furtherly affect the denitrification reaction. From the No.11 to the No.12 test point, the DO concentration increased rapidly, ranging from 1.13 mg/L to 2.23 mg/L. The results showed that the oxygen consumption capacity of microorganisms in this area decreased, and the opening of aeration pipeline could be reduced.

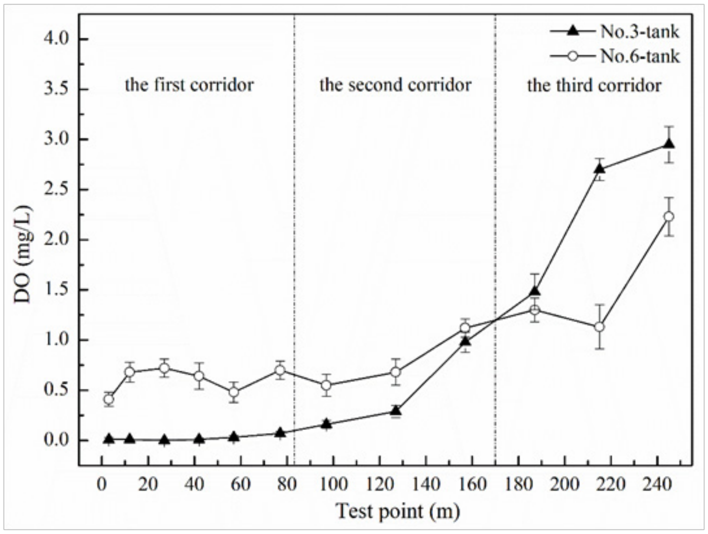

Figure 4: The change of DO Concentration along the Aerobic Tank

The results of OUR and DO show that the oxygen supply in the first two corridors basically meets the oxygen demand capacity, but the aeration capacity of the third corridor is significantly greater than the demand, which result in a waste of energy. On the premise that the complex automatic control program is not introduced into the WWTP, most operation engineers adopt the mode of subsection gradually reducing aeration and control the aeration volume by manually regulating the valve. However, the DO value of each section of subsection decreasing aeration is often determined according to experience, and there is no scientific and clear index to guide the subsection of aeration. Therefore, it is necessary to put forward scientific regulation indicators and control strategies according to the actual degradation law of pollutants and biological treatment systems with different efficiency, so as to provide practical guidance for the upgrading and transformation of WWTPs.

Analysis of Physical-Chemical Indexes

(1) Analysis of Physical-Chemical Indexes of Activated Sludge

In this study, the portable analyzer was used to test the oxidation-reduction potential (ORP), pH and other indexes of these twelve test points in the aerobic tank. The results of these physical-chemical indexes are shown in Table 2.

Table 2: Basic Operation Indexes of Aerobic Tank

Test point (m)	No.3-tank				NO.6-tank			
	MLSS mg/L	MLVSS mg/L	pH	ORP (mV)	MLSS mg/L	MLVSS mg/L	pH	ORP (mV)
3	3652	1991	6.91	-96.8	4676	2899	6.802	87
12	3830	2183	6.918	-98.1	4820	3088	6.805	74.5
27	3764	2045	6.898	-91	4535	2811	6.771	80.5
42	4081	2326	6.892	-83.8	4609	2757	6.738	83.6
57	4175	2179	6.887	-65.1	4818	2887	6.702	82
77	4027	2295	6.885	-12.8	4599	2951	6.675	95.1
97	3970	2262	6.857	24.9	4605	2855	6.693	90.2
127	4013	2187	6.793	68.3	4734	2905	6.603	97.4
157	3851	2195	6.756	102.2	4528	2707	6.636	108.3
187	3709	2154	6.739	110.7	4601	2852	6.512	116.7
215	3578	2099	6.688	164.3	4492	2885	6.461	120.4
245	3659	2018	6.67	213.5	4735	2915	6.421	135.2

The MLVSS/MLSS ratio is commonly used to evaluate the activated sludge activity. In municipal WWTPs, the MLVSS/MLSS ratio is often determined as about 0.75 [22, 23]. Test results of sludge concentration along the corridor were shown in Table 2. The MLSS was ranging from 3578 mg/L to 4174 mg/L, 4492 mg/L to 4820 mg/L in the No.3-tank and No.6-tank respectively, which shows that the systems have good flow pushing effect. Moreover, the MLVSS/MLSS are 0.56 and 0.62 respectively. Studies have shown that the influent sediment concentration has an important effect on the accumulation of inorganic solids and the recovery of activated sludge system. Lower MLVSS/mixed could show that not only reduces the available tank volume but also increases operating costs.

The ORP reflects an oxidation or reduction state of the activated sludge mixture, and it can reflect the denitrification environment and whether adjustments need to be made to change them [24]. ORP index is more sensitive than DO, and it has a stronger indicative effect in biochemical treatment system. As shown in Table 2, ORP in the No.3-tank varies widely, and test points in the first corridor all are negative, ranging from -96.8 mV to -12 mV, and the lowest ORP at the inlet end is close to -96.8 mV. With the increase of process, the change trend is consistent with the change of DO. After entering the second corridor, ORP increased to a positive value, and nitrification was mainly carried out in this stage. At the end of the third corridor, ORP increased to 200 mV. The ORP began to rise significantly after 77 m in the front of the pool, indicating that the tank was in anoxic state at 60 m in the front. The overall DO value of the No.6-tank is high, and ORP basically positive, with little change trend. The results showed that the aerobic environment in the front of the No.6-tank was better, and the nitrification effect was better than that in the No.3-tank.

The alkalinity is an important factor affecting nitrification and dentification reaction, the relative bacteria are very sensitive to pH. Under neutral or slightly alkaline pH conditions (pH 8~9), their biological activity is the strongest and nitrification process is rapid. When pH>9.6 or pH<6.0, the biological activity of nitrifying bacteria will be inhibited and tend to stop. Under acidic conditions, when pH<7.0, the nitrification rate slows down. When pH<6.5, the nitrification rate slows down significantly. When pH<5, the nitrification rate was close to zero. As shown in Table 2, it can be seen that the pH decrease range of the No.6-tank is larger than that of the No.3-tank, which indicates that the nitrification effect of the former is better than that of the latter, and the pH at the end of the No.6-tank is lower than 6.5, which indicates that the nitrification rate of the No.6-tank is obviously decreased. This conclusion is consistent with the change of DO. On the whole, the pH of the two aeration tanks were in acidic condition, and the overall nitrification effect was not ideal.

(2)Analysis of Water Quality along the Corridor

Through the analysis of water quality along the corridor, the degradation regulation of pollutants in the aerobic zone can be investigated, and it can be linked with the aeration performance, activated sludge performance and physic-chemical indexes of the aeration system to evaluate the improvement potential of the treatment capacity of the biochemical system. In this study, water samples were taken at the corresponding test points to test the concentrations of CODCr, NH3-N, TN, and TP, and the treatment effect of the aerobic tank was analyzed and evaluated according to the change regulations. Through the comprehensively comparison, it can be found that the change regulation of wastewater index test results better echoes the activated sludge activity status, while the change of OUR is more forward and more sensitive than the change of concentration of the water quality.

The water quality test results of the No.3-tank and No.6-tank in ZY-WWTP are shown in Fig. 5. The concentration of CODCr decreases from 40 mg/L to 27 mg/L at the outlet, and the removal rate is 32.5%. The NH3-N concentration decreased from 22.41 mg/L to 13.12 mg/L, but there was a weak rising stage in the front, and the removal rate was 41.45%. The nitrification effect was poor, which was consistent with the insufficient aeration and acidic pH value of the No.3-tank. The TN concentration decreased from 35.82 mg/L to 25.45 mg/L, and the removal efficiency was poor, mainly due to the higher ORP in the anoxic zone and the general anoxic environment, which led to the weak denitrification ability. The removal rate of TP was 95.04% when the concentration of TP ranged from 5.24 mg/L to 0.26 mg/L. The degradation process mainly occurred at the end of the first corridor and the second corridor. In the pool section where DO value began to rise at about 100 m, TP began to decrease significantly, indicating that a good phosphorus absorption reaction was carried out.

The results of water quality in No.6-tank of ZY-WWTP are shown in Fig. 5(b). The COD_{Cr} concentration of influent was relatively low, showing a downward trend from 55 mg/L to 36.2 mg/L, with a removal rate of 34.18%. The removal rate of NH_3-N was 97.98% when decreased from 13.34 mg/L to 0.27 mg/L. The change of TN was very small, decreased from 24.66 mg/L to 21.47 mg/L, which decreased by 12.9%. The concentration of TP decreased from 1.62 mg/L to 0.25 mg/L, which was reduced by 84.57%. It reached the standard in the second corridor, and the effluent of the last section was basically unchanged. According to the results of aeration rate and OTE, the No.6-tank has better aeration effect than No.3-tank, which makes No.6-tank have a better aerobic environment, and the removal rate of NH_3-N and TP is better than No.3-tank.

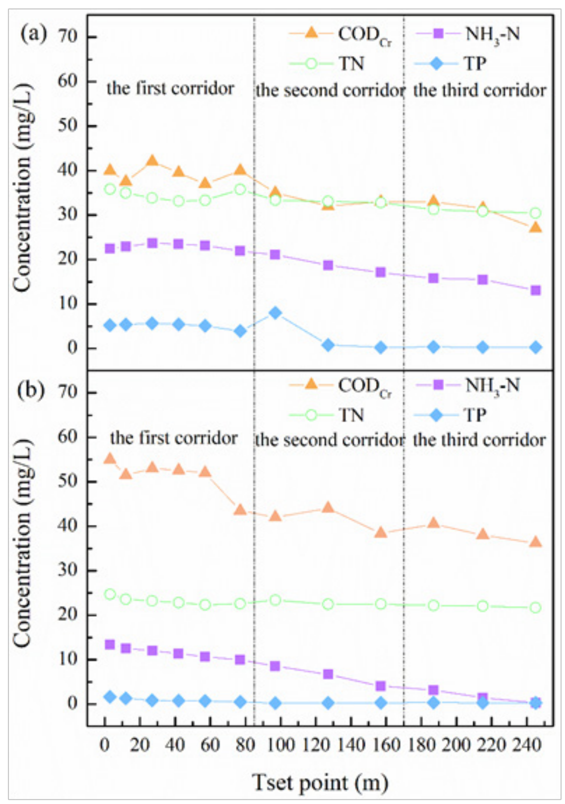

Figure 5: The Change of Water Quality along the Corridor(a) No.3-tank and (b) No.6-tank.

From the above analysis, it can be seen that the scientific operation of aeration system directly determines whether the living environment of microorganisms is suitable, the activity of activated sludge and the effluent quality. Due to the poor aeration effect of the No.3-tank in ZY-WWTP, the DO in the middle and front section is low, which affects the nitrification effect. Cleaning or replacing the aeration equipment, improving the OTE and optimizing the aerobic environment are conducive to the complete nitrification. Taking the first A level an discharge standard as the limit, the NH_3-N concentration still has a reduction potential of at least 8 mg/L. After entering the third corridor, the DO increased gradually in the No.3-tank and No.6-tank of the ZY-WWTP, and the DO at the end was close to 3 mg/L. Because of the low aeration efficiency and the high OUR of activated sludge, the DO concentration of the front end is very low; However, the higher DO value in the end section will lead to higher DO concentration in the reflux and destroy the anoxic environment. In order to ensure the anoxic environment, the amount of aeration in the last stage should be reasonably controlled, and the TN concentration still has the potential to reduce at least 10 mg/L. The efficient operation of biological treatment system is inseparable from the monitoring and diagnosis of aeration system. Only by accurately understanding the operation status of biochemical tank can the efficient operation of the whole system be scientifically guided.

Maintenance and Management of Aeration System

After long-term operation, the aeration equipment in aerobic tank will have pollution and blockage problems, which will lead to the decrease of the OTE in aeration system and the increase of energy consumption in wastewater treatment operation. The process of this kind of problem is slow, and it is difficult for operators to judge by naked eyes in a short time. When the damage of the aerator is completely reflected on the surface of the aerobic tank, the treatment effect of the WWTP has been seriously reduced, and the operation cost has caused a lot of waste. In addition, in order to avoid Not-In-My-Back-Yard, the government has strengthened the control of odor emission from WWTPs in recent years, and the fully enclosed aeration tank is gradually implemented, which further increases the operation difficulty of biochemical tank. The long-term monitoring of the aeration system by using the process state aeration performance tester and the long-term monitoring of the activated sludge activity and influent toxicity by using the specific oxygen uptake rate online monitoring device can scientifically and timely guide the efficient operation of the biological treatment system.

Through the system evaluation of the instrument, the lower aeration efficiency point of the aeration system can be obtained, so as to guide the maintenance or transformation of the aeration equipment. On the basis of field test, the average OTE of the No.3-tank is 26.93%, which is lower than the average. That is, there are at least six test points where the aerator needs to be cleaned or replaced. The average OTE value of the No.6-tank is 25.52%, there are at least three test points where the aerator needs to be cleaned or replaced. Through the replacement of aeration equipment and scientific and effective maintenance, the theoretical maximum aeration efficiency can be increased by 7%. For different pollutants, there are different DO requirements for organic matter degradation and NH_3-N degradation, while in plug flow aeration tank, there are different degradation rules and oxygen demand in space. Through the above field test and OUR analysis results show that the variation trend of OUR is significantly related to the variation trend of pollutants, and OUR is more sensitive than that of pollutants. For the organic matter degradation section, relevant research and experimental verification show that when other operating conditions are in a reasonable range, no matter DO is 2 mg/L or 0.5 mg/L, organic matter can be degraded rapidly. Therefore, DO at 0.5 mg/L can meet the demand of heterotrophic bacteria. For the NH_3-N degradation stage, DO should be maintained at about 2 mg/L in order to ensure the NH_3-N degradation effect.

Results of the balance of oxygen in supply and demand in aerobic tank were shown in Fig. 6. Under the current operating conditions, the oxygen in supply (Qs) are about 440, 309 and 241 kg/h, while the oxygen in demand (Cs) are 81, 355 and 448 kg/h respectively in the three corridors of the No.3-tank. Similarly, the Qs are about 440, 309 and 241 kg/h, while the Cs are 309, 266.3 and 245.3 kg/h respectively in the No.6-tank. Results showed that these two aerobic tanks generally have the problems of insufficient aeration at the front end and residual aeration at the back end. Based on the process state aeration performance tester and the specific oxygen uptake rate online monitoring device, the Qs and Cs can be accurately monitored and evaluated. Through the analysis of the measurement process and results, more scientifically and reasonably aeration was regulated, which ensure that the biological treatment system can not only meet the effluent quality standards, but also achieve energy saving and consumption reduction.

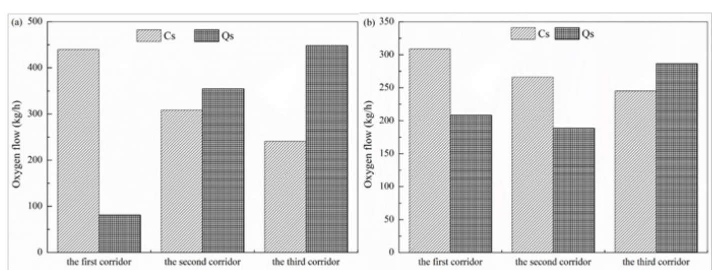

Figure 6: Analysis of the Balance of Oxygen in Supply and Demand in Aerobic Tank No.3-tank and (b) No.6-tank.

For different pollutants, the degradation of organic matter and NH_3-N have different requirements of DO, but in the plug flow aerobic tank, it shows different spatial degradation regulations and different oxygen in demand. Combined with the above experiments and analysis, the following subsection regulation strategies could be proposed: (1) Measuring the influent water quality or analyzing the historical data of the WWTP to determine the CODCr and NH_3-N concentrations at the head end of the aerobic tank. (2) According to the pollutant concentration at the head end of the aerobic tank, the subsection applicability of aeration control is analyzed to determine the subsection mode. (3) Using the specific oxygen uptake rate online monitoring device, the model of OUR and pollutant degradation rate is tested and established, the test points of aeration control aeras are determined, and the length of each aera of the aeration tank is calculated. (4) According to the degradation characteristics of pollutants in each section, set the optimal DO level and establish aeration control countermeasures. The optimal DO is not only can provide enough oxygen for the degradation of pollutants, meet the normal physiological metabolism of microorganisms and realize the removal of pollutants, but also ensure the minimum amount of aeration, so as to achieve the lowest energy consumption.

Conclusion

By analyzing the balance of oxygen in supply and demand in ZY-WWTP, the followingconclusions can be drawn:

1. The OTE were 26.93% and 25.52% in the No.3-tank and No.6-tank respectively, are all far lower than the OTE value (40%) under clean water. Combined with the results of OTE and I_{AU}, aerators where the No.1, No.2, No.3, No.4, No.5, No.10 in the No.3-tank, the No.6, No.7, No.9 in the No.6-tank need to be repaired or replaced.
2. Based on the principle of oxygen balance, the Qc is insufficient at the front end of the aeration area, but it is excessive at the rear end. Reducing the aeration volume at the end of the aerobic tank, controlling the DO concentration of reflux and restoring the functions of anoxic zone can improve the removal efficiency of pollutants.
3. The subsection regulation strategy is to determine the subsection pattern and subsection point of aeration control based on the pollutant degradation characteristics, and then determine the optimal DO concentration based on OUR and pollutant degradation model.

Informed Consent

Informed consent was obtained from all individual participants included in the study.

Compliance with Ethical Standards

This study has complied with all ethical standards at all phases of research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Credit Author Contributions Statement

Jingbing Zhang and Yuting Shao: designed the research and performed the experiments. **Wenzhuo Sun:**visualization. **Zhao Jiang:** analyzed the data. **Lu Qi:** drafted the manuscript. **Guohua Liu:** revised the manuscript. **Hongchen Wang:** reviewed and edited the manuscript.

Data Availability Statements

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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