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EVALUATION OF THE APPLICATION AND OPERATIONAL PERFORMANCE OF THE MODIFIED MULTISTAGE AO PROCESS IN A SEWAGE TREATMENT PLANT

The multistage anoxic/oxic (AO) process is widely known for its effectiveness in wastewater treatment, serving as a core technology in numerous wastewater treatment facilities. Its application in the expansion project of the sewage treatment plant in Dongguan City is particularly noteworthy and merits further research into its performance. To validate its reliability, we conducted a monitoring experiment spanning over 200 days. The results revealed that under stringent operational conditions, the plant demonstrated significant stability in ensuring the effluent quality meets grade A standards. Additionally, its removal efficiency for various pollutants exceeds 90%, particularly outstanding in nitrogen and phosphorus reduction, even when the total phosphorus in the influent exceeded the standard by 2.6 times, the effluent remained stable. These compelling pieces of evidence highlight the superiority of the multistage AO process, positioning it as the preferred technology for widespread adoption in the expansion of wastewater treatment plants. This study can provide valuable insights for the construction of other sewage treatment plants.

1. INTRODUCTION

Over the past century, the activated sludge process has evolved significantly as a cornerstone of domestic sewage treatment. Initially relying on primary activated sludge techniques, it has gradually transformed into advanced sequencing batch-activated sludge processes like sequential batch reactor (SBR) and cyclic activated sludge system

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(CASS), along with their derivative technologies. Moreover, improvements like membrane bioreactor (MBR) and anaerobic ammonium oxidation (ANAMMOX) have further enhanced the performance of activated sludge treatment [1, 2]. Today, each of these processes finds its niche in specific scenarios, exhibiting remarkable sewage treatment capabilities [3–5]. Among these advancements, the multistage anoxic/oxic (AO) process stands out as a particularly efficient technology, often serving as the core of wastewater treatment plants. In a recent expansion project at a sewage treatment plant in Dongguan City, the multistage AO process was employed, and its application was thoroughly evaluated. Under real-world operating conditions, the plant was able to stably achieve Grade A effluent standards, with pollutant removal rates exceeding 90%, demonstrating excellent nitrogen and phosphorus removal. This underscores the superiority of the multistage AO process and its vast potential for wider application in the expansion of wastewater treatment facilities.

As environmental protection standards in China become increasingly stringent, the quality requirements for effluent water from sewage treatment plants have also escalated across various regions. Many areas have mandated that the effluent water from sewage treatment plants must adhere to the primary A standard of the *Urban Sewage Treatment Plant Pollutant Discharge Standard (GB18918-2002)*. In some cases, even stricter standards are imposed, requiring certain discharge indicators to meet Class IV surface water standards. These new requirements have posed significant challenges to urban sewage treatment plant technology, catalyzing the innovation and advancement of sewage treatment methodologies. Currently, refined processes like the multistage AO process and the multi-point influent inverted AO process have emerged, enhancing the traditional activated sludge process and significantly boosting its wastewater treatment efficiency [6–8].

This work examines the expansion project of a sewage treatment plant in Dongguan City, comprehensively considering regional planning, construction, and the operational status of the existing facility. Commencing with the design of water quality parameters and aiming to achieve the specified effluent discharge standards, the paper delves into the technological process and the determination of key parameters for the primary structural units. Additionally, it evaluates the operational performance of the expanded plant, aiming to provide valuable insights and references for the upgradation and expansion of sewage treatment plants in other regions.

2. PROJECT OVERVIEW

The first phase of the sewage treatment plant in Dongguan, completed in 2013, currently operates at a treatment scale of 40 000 m^3/day, employing the anaerobic-anoxic-oxic (AAO) process. The effluent quality adheres to the stricter values set in the first class A standard of the *Urban Sewage Treatment Plant Pollutant Discharge Standard (GB18918-2002)* and the second phase of the first class standard in the local standard of Guangdong Province (DB44/26-2001). However, due to the rapid urban development, the original plant has been operating at full capacity for an extended period, resulting in sewage overflow issues in the current pipe network, posing potential pollution risks to the surrounding environment. Therefore, an expansion project has become imperative.

The following issues were identified in the original sewage treatment plant: (1) long-term overload operation has led to high pressure on facility operation and maintenance; (2) the automation level of secondary treatment is low, and the treatment effect cannot be visually monitored; (3) given the high demand for total phosphorous (TP) treatment in this region, the lack of stable and reliable chemical phosphorus removal units in the first-phase project poses potential risks for TP standards in long-term operation.

The existing issues in the current Phase I project, coupled with a comprehensive analysis of the water quality and quantity trends within the service area, have led to the determination that the expansion project will adopt an improved multistage AO process. The designed treatment scale has been set at 30 000 m^3/day. After the completion of the expansion, the total treatment capacity of the sewage treatment plant will reach 70 000 m^3/day. The design effluent of the expansion project must adhere to the stringent level A *standard of the Urban Sewage Treatment Plant Pollutant Discharge Standard*, as well as the level I standard of the *Guangdong Provincial Local Standard of Water Pollution Discharge Limit* in the second phase. Specifically, the ammonium nitrogen index should not exceed 1.5 mg/dm^3 and the total phosphorus index should not exceed 0.3 mg/dm^3. The main water quality parameters are given in Table 1.

Table 1

Main designed influent and effluent quality [mg/dm^3]

Index	COD_{Cr}	BOD_5	SS	NH_4^+-N	TN	TP
Influent quality	300	130	200	30	40	4.5
Effluent quality	40	10	10	1.5	15	0.3

Given the stringent effluent requirements of this project, it is imperative to augment the secondary treatment with an advanced treatment process to significantly enhance the nitrogen and phosphorus removal efficiency. Specifically, achieving a total phosphorus concentration below 0.3 mg/dm^3 in the effluent poses a challenge, making biological phosphorus (TP) removal alone insufficient.

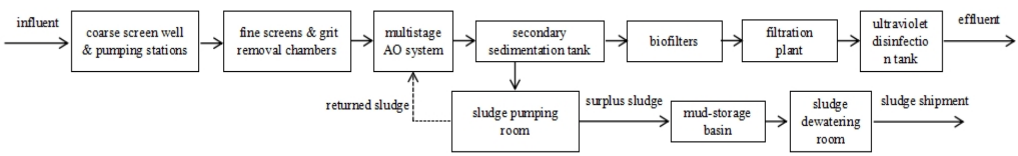

Fig. 1. Flow chart of the sewage treatment process

Thus, the concurrent utilization of chemical phosphorus removal methods is necessary. Consequently, the overarching objective of the entire engineering design is to guarantee the smooth functioning of the biochemical system, bolstered by chemical methods, to ensure water discharge meets all standards. The inclusion of a press cloth filter serves a dual purpose: it not only improves the removal of suspended matter (SS) but also aids in the elimination of COD and total phosphorus, thereby ensuring all indicators adhere to the discharge regulations. Taking these considerations into account, the processing procedure for the expansion project has been finalized as shown in Fig. 1.

3. DESIGN OF MAIN STRUCTURES

3.1. MULTISTAGE AO SYSTEM

As the pivotal component of this expansion project, ensuring the biochemical system's normal operation is crucial for the sewage treatment plant to meet all discharge standards. Its well-thought-out design is paramount to the success of this undertaking. Taking into account the comprehensive factors of sewage generation, water quality, and effluent requirements in the service area, the enhanced multistage AO technology has been selected for this process. This technology efficiently provides carbon sources and nitrates for anaerobic phosphorus release, denitrification, and nitrogen removal, thereby significantly enhancing the overall treatment efficiency. The multistage AO process is depicted in Fig. 2.

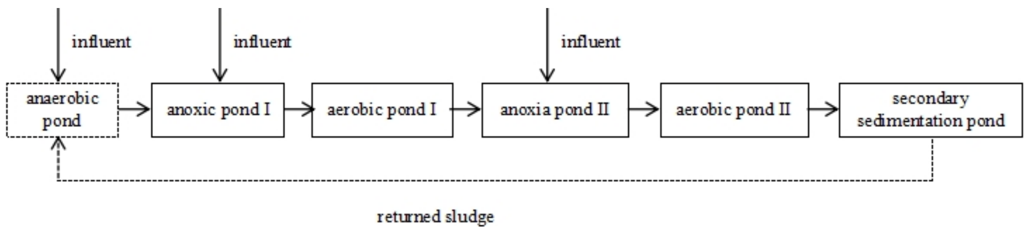

Fig. 2. Flow chart of the improved multistage unit

Zhou et al. [9] proposed an innovative step-feed three-stage integrated anoxic/oxic biological aerated filter system to improve nitrogen removal efficiency in synthetic domestic wastewater treatment. Experimental results demonstrated that optimal nitrogen removal performance was attained with influent flow distribution ratios of 3:5:2 across the three-stage reactors. Cheng et al. [10] constructed a multistage high-efficiency anaerobic-aerobic biofilm reactor and improved the nitrogen removal capacity of the system by varying the number of A/O stages, influent, and hydraulic retention time (HRT). The results demonstrated that the most economic system with the desired total nitrogen

(TN) removal was found to be a three-stage A/O with a step feed ratio of 1:1:1 and HRT = 36 h. Gong et al. [11] established pilot-scale anaerobic-oxic-anoxic (AOA) and anaerobic-anoxic-oxic (AAO) systems with long SRT (30 days) in parallel to treat actual urban wastewater. The results indicated that the sludge reflux ratio significantly impacted the nitrogen and phosphorus removal performance of the AOA and AAO systems. The optimal performance of the AOA system was achieved at a sludge reflux ratio of 200%, resulting in COD, NH_4^+-N, TN, and TP removal ratios exceeding 90%. Wang et al. [12] found that the residence time and inflow flow ratio can significantly affect the nitrogen load and organic matter distribution at each stage of the multistage AO system. Under optimal conditions, the removal rate of ammonia nitrogen at each stage of the system is above 80%, and the total nitrogen removal rate is above 80%.

By referring to relevant literature and combining it with the actual pilot and pilot test data, a new biochemical reaction tank of the multistage AO process was built in the project. The design scale of the tank body was 1750 m^3/h (42 000 m^3/day), the plane dimensions were 63.4 m, 81.2 m, and 8.5 m, respectively, and the effective water depth was 7.5 m. The effective capacity of a pool was 37 500 m^3. The pool capacity was divided into the anaerobic zone, anoxic zone of the first stage, aerobic zone of the first stage, anoxic zone of the second stage, and aerobic zone of the second stage, and the residence time was 2, 4.5, 8, 2 and 0.5 h, respectively. Other major parameters of the multistage AO system are given in Table 2.

Table 2

Design parameters of the treatment units

Sludge concentration	Age	Internal reflux ratio	External reflux ratio	Theoretical gas supply	Gas to water ratio	Total residence time
3.5 g/dm^3	25 days	250%	100%	100 m^3/min	5:1	17 h

3.2. DESIGN PARAMETERS OF OTHER MAIN PROCESSING UNITS

In addition to the multistage AO system, other processing units all adopt common process facilities. The pretreatment units are a coarse grid, a lifting pump, a swirl sedimentation tank, and a fine grid. An emergency storage tank is installed before the effluent enters the biochemical system so that adjustments can be made in advance in the event of excessive water volumes or fluctuations in water quality. The secondary sedimentation tank uses the radial sedimentation tank surrounding the central gold water, and the rear end is connected with the filter cloth filter as the depth treatment unit. Air suspension centrifugal blower is used for blower (simple installation, low energy consumption, low noise, and easy maintenance), and centrifugal dehydrator is used for sludge dewatering. Specific design parameters are shown in Table 3.

Table 3

Design parameters of the treatment units

Unit	Parameters
Emergency storage tank	an underground emergency reservoir with a diameter of 30 m and a depth of 5 m
Coarse screen well and upgrading pumping stations	two submersible centrifugal pumps, frequency conversion control, the flow of 1100 m^3/h, the pump head 18.5 m, the power of the set of 110 kW
Fine screens and grit removal chambers	hole plate fine grid 1, grid channel width 2100 mm, width 1950 mm, the smoke control diameter of 5 mm, and the power of a single set of 2.2 kW
Secondary sedimentation tank	two radial sedimentation tanks with a diameter of 38 m and depth of 4.5 m, designed average surface load of 0.92 m^3/m^2h, and peak residence time of 4.1 h
Biofilters for denitrification	two sets of press cloth systems (24 in total), a diameter of 3 m, the processing capacity of each set of 1792 m^3/h, the peak filtration rate less than 10 m/h, and the backwashing rate of 7.7 dm^3/s
Aerating system	three centrifugal blowers (two used and one standby) are used, each with a flow of 90 m^3/min, wind pressure of 85 kPa, and power of 185 kW
Reagent feeding system	phosphorus removal agents: poly aluminum chloride, flocculant: polyacrylamide, disinfectant: sodium hypochlorite
Sludge treatment system	mud storage tank: one block is divided into two cells, each cell holds 4 h of mud, the plane size is 8×8 m, the depth of the tank is 5 m, and the two cells switched to be used as a mud storage tank and a conditioning tank; deep dewatering machine room equipped with two sets of plates and frame filter press, filter area of about 600 m^2, feed pressure ≤1.2 MPa, press pressure ≤1.8 MPa

3.3. ENGINEERING DESIGN FEATURES

The project employs a multistage AO process, which divides the sewage treatment into multiple stages alternating between anoxic and aerobic sections of the biological tank. By introducing return sludge into the front end, a concentration gradient from high to low is created, resulting in a higher average sludge concentration within the biological tank. This alternating environment fosters a more conducive growth habitat for phosphorus-accumulating bacteria, nitrifying bacteria, and denitrifying bacteria, thereby enhancing the efficiency of nitrogen and phosphorus removal. Consequently, the required biological tank volume is reduced, leading to a corresponding decrease in project investment.

As the wastewater traverses the multistage anoxic/aerobic environment, the processes of nitrification and denitrification occur alternately. This approach maximizes the utilization of the carbon source present in the wastewater, minimizing the reliance on external carbon sources. Furthermore, it mitigates sludge bulking, enhances sludge settling properties, and improves the sedimentation efficiency of the secondary sedimentation tank.

4. EVALUATION OF THE PROJECT PERFORMANCE

The expansion project for the sewage treatment plant in Dongguan, which commenced construction in 2018, was set to be completed and operational by February 2020. Currently, the intake load remains consistently above 90%, and the maximum daily treatment capacity surpassed 130%. While there were occasional anomalies in the influent water quality, where ammonium nitrogen and total phosphorus (TP) exceeded standards, the overall C/N ratio remained low. Nevertheless, the effluent quality remained consistently stable, meeting all discharge standards. Figure 3 illustrates the water quality and removal rates of the project over 207 days, from April 1 to October 24, 2020.

The collection of water samples and water quality testing involved in this project were conducted under the *Ecological Environmental Standards of China* (*Technical Specifications for Wastewater Monitoring, HJ 91.1-2019*). To ensure the stability of the experimental results, we sampled water for testing at 09:00, 15:00, and 21:00 every day and took the average of the three results as the water quality data of the day.

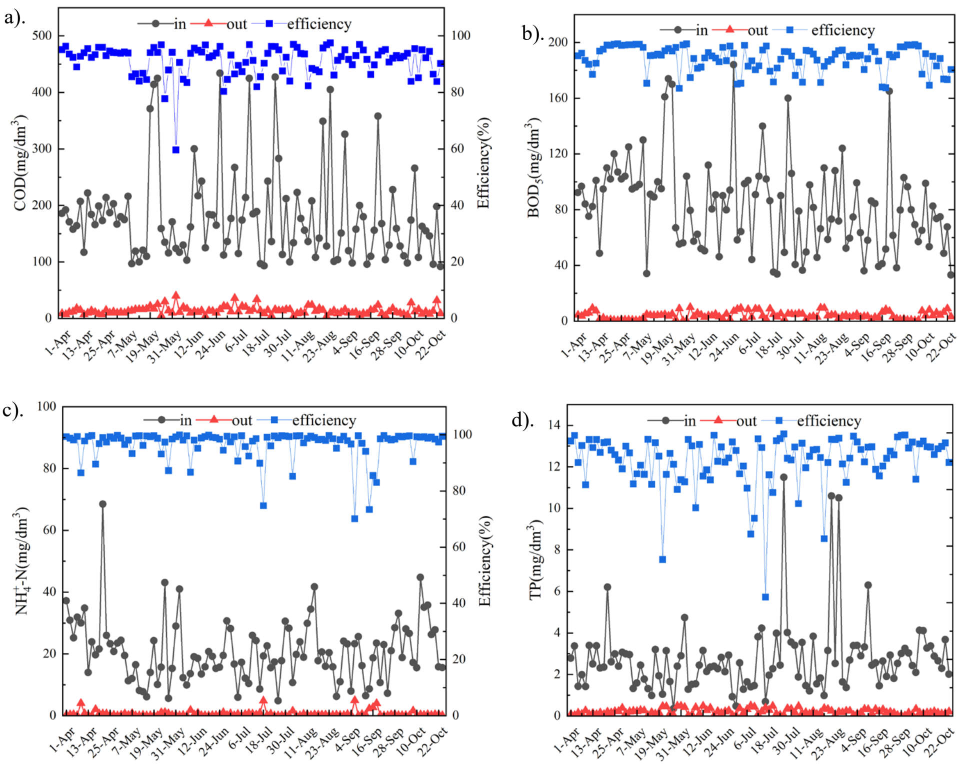

Fig. 3. Efficiency of the improved multistage unit
on the removal of: a) COD, b) BOD_5, c) NH_4^+-N, d) TP

From the overall results, the main effluent quality index of the current expansion project can stably meet the design requirements. During the whole monitoring period, the average COD, BOD_5, NH_4^+-N and TP of effluent were 14.04, 4.08, 0.59 and 0.21 mg/dm^3, respectively; the maximum values were 40, 10, 4.96 and 0.5 mg/dm^3, respectively; the average removal rates were 92.26, 95.08, 97.17, and 92.37%, respectively.

The main wastewater quality of the incoming wastewater exceeded the design value in some time, and even exceeded the standard by 2.6 times at some time points (total phosphorus value was 11.5 mg/dm^3 on July 26) (Fig. 3). However, the effluent could reach the standard stably, demonstrating excellent impact load resistance. The reason is that when the data of total phosphorus was found to increase abnormally, the research results of references [13, 14] adjusted the operating conditions in time, adopted the strategy of phosphorus removal as the main, adjusted and increased the internal reflux flow of anaerobic section and the wastewater intake of anoxic section, and formed an operation mode similar to inverted AO. At the same time, supplemented by the addition of phosphorus removal agents, enhanced the phosphorus removal effect of the biochemical system. Ensure the quality of effluent water.

5. CONCLUSION

- For the current expansion project, taking into account the actual inflow characteristics and aligning with the effluent quality standards, the enhanced multistage AO process was chosen as the primary biochemical system, resulting in exceptional sewage treatment outcomes.
- During system operation, despite occasional fluctuations in incoming wastewater quality, the effluent index of the entire system remains largely unchanged, exhibiting a notably robust ability to withstand impact loads.
- In response to wastewater quality variations, the nitrogen and phosphorus removal efficiency of the system can be enhanced by adjusting the proportion of influent flow and internal/external recycle flow at each stage. This ensures stable effluent discharge that meets standards.
- This study offers valuable insights and serves as a reference for treating domestic sewage with a low C/N ratio in real-world applications.
- It is anticipated that future work will involve further optimisation of the process parameters and improvement of the system automation level. This will facilitate more efficient and stable operation of the system, as well as enhancing the overall performance of the system.

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