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Pilot study on urban sewage treatment with micro-pressure double-cycle reactor

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ABSTRACT

To solve the practical problem of difficulty in upgrading the standard of the urban sewage treatment plant caused by the high concentration of influent suspended solids (SS) and the low temperature of the influent, this study designed a new type of micro-pressure double-cycle reactor (MPDR). The fluid state simulation test and the pilot test of urban sewage treatment were carried out in the experiment. The results showed that, under the condition of aeration of 0.2 m^3/h, MPDR could form two circulation flows in the reactor to achieve the circulation of the materials. The pilot test research showed that MPDR could achieve high efficient removal of SS, chemical oxygen demand, NH_4^+–N, total nitrogen, total phosphorus under the conditions of drastic fluctuation in inlet water quality and drastic change in inlet water temperature. The average effluent concentration of each index was 48.60, 26.26, 0.57, 8.72, and 0.17 mg/L, which better than the Class A discharged standard of the Chinese urban sewage treatment plants. The analysis of the microbial flora showed that the rich content of *Dechloromonas* was an important reason for the high-efficiency nitrogen and phosphorus removal of the MPDR pilot test device. Moreover, there was a difference in the spatial distribution of the microorganisms in the reactor, and the aggregation distribution of microorganisms with different functions improved the space utilization of the reactor. The results of the study proved that MPDR solved the practical problem well, and it could provide a new way for the upgrading of urban sewage treatment plants.

Keywords: Micro-pressure double-cycle reactor; Pilot test; Microbial flora; Flow pattern simulation; Urban sewage

1. Introduction

Urban sewage treatment plants play a vital role in reducing water pollution and protecting water resources. But in recent years, studies have shown that the eutrophication of surface water near many cities is caused by the effluent from urban sewage treatment plants [1–3]. To prevent the above-mentioned situation from deteriorating, relevant departments in China have formulated stricter emission standards for nitrogen and phosphorus in urban sewage

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treatment plants. However, for some urban sewage treatment plants in Northeast China, it is almost impossible to increase the emission standards of nitrogen and phosphorus. There are mainly the following reasons. First of all, the design and treatment facilities of the sewage treatment process are backward. It is difficult to further improve the removal efficiency of nitrogen and phosphorus. Secondly, the temperature of influent in Northeast China in winter is generally 8°C–10°C. The low temperature will seriously hinder the nitrification process and lead to the difficulty of nitrogen removal [4]. Also, some urban sewage treatment plants will cause a sudden increase in the concentration of suspended solids (SS) in the influent when the snow and ice melt in spring and heavy rain in summer, which will not only impact the biochemical aeration tank, but also cause the sedimentation tank to be seriously overcharged, and eventually lead to excessive nitrogen and phosphorus in the effluent [5]. Therefore, it is of great practical value and significance to find a reasonable and effective urban sewage treatment plant transformation method suitable for Northeast China.

The micro-pressure double-cycle reactor (MPDR) is a new type of sewage treatment process suitable for the upgrading and reconstruction of urban sewage treatment plants based on years of research, practice, summary, and design by our research team. At present, the urban sewage treatment plants in Northeast China that are difficult to upgrade the standard are mainly with a single-tank structure, such as the traditional activated sludge method and the cyclic activated sludge technology process. The disadvantage of this type of process is the lack of an anaerobic environment during the biochemical reaction. In recent years, researchers have invested a lot of effort to create an anaerobic environment in the biochemical aeration tank. However, most of the reported improvement processes were too complicated, and it was difficult to transform the actual sewage plant [6,7]. In the existing research, by simply improving the traditional biological aeration tank, a micro-pressure swirl reactor (MPSR) was formed, and which could exist three different dissolved oxygen (DO) environments (anaerobic, anoxic and aerobic) in a single aerated biological tank. Meanwhile, the MPSR was also excellent in the treatment of low-temperature sewage, aeration energy-saving, impact load resistance and simultaneous nitrogen and phosphorus removal [8–10]. The design principle of the MPDR was based on the MPSR, but the MPDR has a design idea that was adapted to local conditions, made it more suitable for the transformation of actual sewage treatment plants. The MPDR used two baffles with an obtuse angle to construct a semi-enclosed area which similar to MPSR in the aeration tank, while placed the aeration device on the side close to the baffle. Two circulation flows were formed in the area separated by the baffle by aeration drive. The MPDR perfectly inherited the characteristics of the MPSR. At the same time, the sedimentation zone was formed at the angle between the baffle and the sidewall of the reactor. When a high concentration SS impact load occurred, it could assist the sedimentation tank and reduced the influence of high concentration SS impact.

At present, the research work on the MPDR is still in the experimental stage. In this paper, the design idea and structure of MPDR were systematically introduced and conducted a fluid state simulation study on its fluid state. At the same time, the pilot test device for MPDR in an urban sewage treatment plant in Changchun had established. Here, the operation and treatment effect of the pilot-scale MPDR was first introduced, then analyzed its operating efficiency, and finally studied the internal microbial structure during the stable operation of the pilot-scale MPDR. The purpose of this article was to reveal the operating efficiency and treatment mechanism of MPDR, thus providing a new solution for the upgrading of urban sewage treatment plants.

2. Materials and methods

2.1. Description of the MPDR

The schematic diagram of the MPDR and the ideal DO distribution in the MPDR was shown in Fig. 1. The MPDR was modified from the traditional biological aeration tank. The baffle plates 1 and 2 were fixed on the sidewall of the aeration tank to form a semi-closed area I. The angle between baffle 1 and baffle 2 ranged from 100° to 120°, which needed to be determined by the ratio of the effective water depth of the aeration tank and the length of the sewage in the flow direction. The smaller the ratio, the greater the angle between the two baffles. Adjusted the original aerator on the bottom of the aeration tank to lie on the side near baffle 1, and set the water outlet on the side near baffle 1 too. Through the above adjustments, the transformation of the MPDR was completed. Fig. 1c shows the distribution of mixed liquid flow direction in MPDR under the ideal working conditions. It could be seen that by driving of single-side aeration, the bubbles in the area I moved along the baffles and drove the liquid flow so that the mixed liquid in the area I was powered and circulated. The semi-sealed structure in the area I could extend the contact time between air bubbles and sewage, thereby improving the oxygen transfer efficiency. Since sewage and air bubbles were mainly in contact with the side near the baffle, under proper aeration condition, not only sewage and activated sludge in this area could be mixed and circulated, but the DO concentration could also be gradually reduced from the surrounding to the center of the area, formed different dissolved oxygen zones (aerobic, anoxic and anaerobic), as shown in Fig. 1d. Area II was the area enclosed by baffle 2 and the horizontal plane. The driving force was obtained by the bubbles leaving baffle 2 and moving vertically upward, thereby forming a small circulating flow in area II. Because the circulation power in this area was small, the activated sludge gradually accumulated and the flow speed was slow. Therefore, area II was prone to form an anoxic environment, and its function was to denitrify the nitrate–nitrogen flowing out of area I. Area III was the area sandwiched by baffle 1 and the sidewall of the reactor. The mixed liquid in this area was basically not in contact with the bubbles, and there was no interference of the aeration power to form a unique sedimentation area in the aeration tank. Meanwhile, at the junction of area III and area I, due to the suction of the aeration, the activated sludge in the sedimentation area could flow back to the main reaction area I. The function of this area was to improve the sludge retention capacity of the system, saved a part of the power

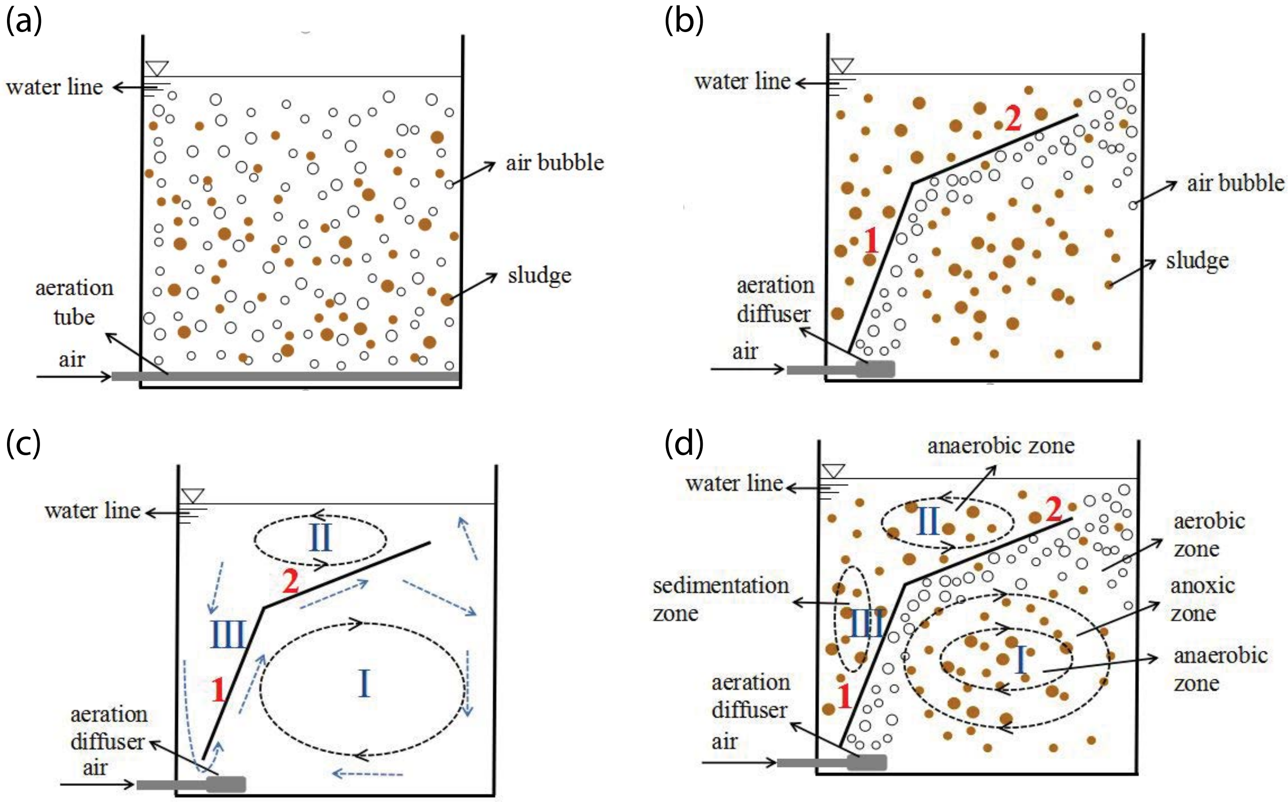


Fig. 1. (a) Schematic diagram of traditional biological aeration tank, (b) schematic diagram of MPDR biological aeration tank, (c) schematic diagram of MPDR mixed liquid flow distribution in ideal state, and (d) schematic diagram of MPDR different dissolved oxygen zones in ideal state.

consumed by the return sludge, and improved the system's resistance to adverse environments. Besides, when the concentration of SS in the influent was high, it could be used as an auxiliary sedimentation area to reduce the impact of the high concentration of SS on the sedimentation tank and ensured the quality of the effluent.

2.2. MPDR flow simulation test

The flow state simulation test model of the MPDR is shown in Fig. 2. The reactor was made of plexiglass plate, it was 800 mm long, 100 mm wide, and the effective height was 800 mm, the effective volume was 64 L. The angle between the two baffles was 120°. The angle between baffle 1 in the reactor and the vertical direction was 20°, and the angle between baffle 2 and the horizontal direction was 10°. The lowest point of baffle 1 was 20 mm from the bottom of the aeration tank and 80 mm from the sidewall. Baffle 1 was 700 mm long and baffle 2 was 600 mm long. The aeration device was placed at the bottom close to the side of baffle 1 and adopted a perforated pipe for aeration. The reactor was aerated through an air compressor (ACO-12, Sunsun, China), and an airflow meter (LZB-DK600-4F, Cheng Feng, China) was used to control the aeration rate at 0.20 m^3/h. The water inlet was also set as a perforated pipe, the installation position was the same as the aeration device, and it was fixed on the reactor with a rubber plug together with the aeration tube.

The flow state simulation test of the MPDR was divided into two parts. First, the numerical simulation software (Workbench 15.0 and Fluent 15.0, ANSYS, USA) was used to simulate the hydrodynamic characteristics of the reactor flow field, and the internal flow field characteristics of the two-phase flow MPDR were simulated. Secondly, by injected pink ink and simulated the actual running state, the photos were taken regularly. Compare the actual water flow morphology photos with numerical simulation flow pattern analysis to verify whether the MPDR has reached the expected flow condition.

2.2.1. Numerical simulation of flow patterns

At present, the literature on numerical simulation showed that the addition of solid particles has little effect on the distribution of liquid velocity in the flow field [11]. In this study, a gas–liquid two-phase flow two-fluid model was selected for numerical simulation calculations. The actual size of the simulated aeration tank was 800 mm long and 800 mm high, and it was open to the atmosphere. The aeration tube was 20 mm from the bottom edge and 100 mm from the left side. The number of perforated aeration tube openings was 25. The study used quadrilateral non-uniform grids. The main parameters were set as follows: relevance center was set to fine, smoothing was set to high, the minimum size was 0.05, proximity minimum size was 0.05, the maximum face was set to 5.0 mm, the

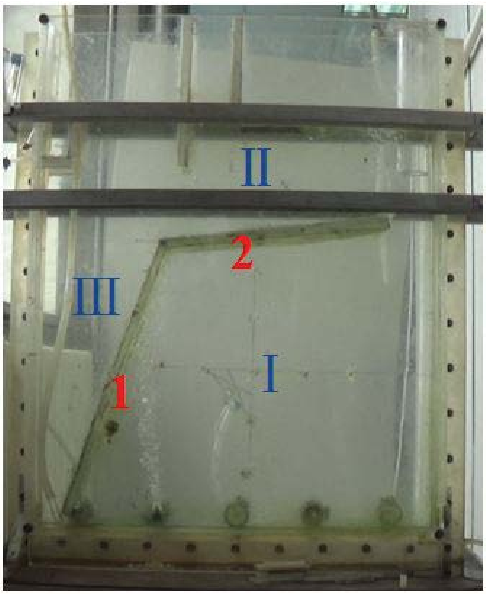


Fig. 2. Model of MPDR internal flow pattern simulation test.

maximum size was set to 10.0 mm. According to the above parameters, there were 32,148 grid nodes and 31,496 grid cells.

2.2.2. Clearwater verification test

Filled the reactor with tap water and started aeration, the aeration amount was 0.20 m^3/h. After the water surface has stabilized, used a peristaltic pump (BT300-2J, Longer Pump, China) to inject red ink through the water inlet pipe for 10 s. The movement of the internal fluid was judged by the movement of the red dye. When the ink entered from the bottom aeration place, started the timer, and the photos when the ink spread was taken at 7, 12, 25, and 35 s, respectively.

2.3. Pilot test of the micro-pressure double-cycle process

To expedite the solution of high concentration of influent SS and enhanced low-temperature sewage denitrification in Northeast China, the pilot test of the MPDR to treat urban sewage based on verifying the flow state of the MPDR was launched. The pilot test device was located in an urban sewage treatment plant in the high-tech development zone in Changchun. Because the influent SS exceeded the design value for a long time, the primary sedimentation tank of the plant was in an idle state. The influent in the pilot test device was the effluent from the fine grille of the plant. The total area of the pilot test device was 36 m^2, and the main components included the water inlet tank, the MPDR, and the sedimentation tank. All structures were made of Q235 steel plate welded on both sides, the structure pool wall and the internal baffle of the reactor were made of 6 mm thick Q235 steel plate, and the reactor bottom plate was made of 10 mm thick Q235 steel plate. The dimensions of the main structure were as follows. The inlet tank with the length was 1,500 mm, the width was 500 m, the height was 1,500 mm, and the effective height was 1,200 mm. The MPDR with the length was 6,000 mm, the width was 3,850 mm, the height was 5,200 mm, the effective height was 4,200 mm, and the effective volume was 97.00 m^3. The sedimentation tank with the length was 3,850 mm, the width was 2,500 mm, the height was 5,200 mm, the effective height was 4,200 mm, and the height of the bottom cone was 900 mm. The lowest point of baffle 1 of the pilot test device was 500 mm from the bottom of the reactor, 500 mm from the sidewall of the reactor, and the angle with the vertical direction was 10°. The lowest point of baffle 2 was 2500 mm from the bottom of the reactor and 1,000 mm from the sidewall of the reactor, and with an angle of 10° to the horizontal. The angle between the two baffles was 110°.

The schematic of the pilot test device is shown in Fig. 3. The sewage was lifted from the fine grid outlet tank of the sewage plant by the inlet pump (CS3045HT 3-252, Xylem, Germany) to the inlet tank of the pilot test device, and then entered the center area of the reactor by gravity flow through the inlet pipe. After the biochemical reaction in the reactor was completed, the sewage flowed into the sedimentation tank through the overflow weir to separate the sludge and water. The return sludge was lifted by the sludge pump (IP900W, Sulzer, Switzerland) to the inlet tank and mixed with the inlet water, and then returned to the system. At the same time, the valve was periodically adjusted to discharge the excess sludge. The effluent in the sedimentation tank was discharged through the drainpipe, and the pilot test device used a rotary blower (HC-509, Best, China) for aeration.

During the start-up phase of the pilot test device, the activated sludge in the aerobic zone of the biochemical tank of the urban sewage treatment plant was inoculated, and the initial activated sludge concentration in the MPDR was maintained at about 8,000 mg/L. After two weeks of continuous cultivation using the closed-loop method, the activated sludge in the reactor tended to stabilize, and the pilot test was started. The pilot test study lasted for one year, and the research test continued from January 22, 2016 to January 22, 2017. During the test, the operating parameters of the pilot test device were as follows. The hydraulic retention time (HRT) was set to about 8 h, so that the influent flow rate was 12 m^3/h. The sludge reflux ratio was set to 50%, and the return sludge flow rate was 6 m^3/h. The aeration rate was designed according to the air-water ratio of 3. Therefore, the aeration rate was 36 m^3/h. The sludge age was set to 30 d. The sludge discharge was determined by measuring the concentration of the returned sludge and the concentration of sludge in the reactor. The aeration rate was controlled by an intelligent vortex flow-meter (LUGB-20 35-P2, Carmen, China). The inlet water flow and sludge flow were controlled by an electromagnetic flow-meter (DM7-FI-80-AC-5, Dephi, China). Daily inspection and maintenance of the pilot test device to ensure the stability of the test operation parameters. The water quality of the pilot test device during the test is shown in Table 1.

2.4. Analysis methods

2.4.1. Routine index detection

During the test period, the influent and effluent water quality indicators of the pilot test device were tested every

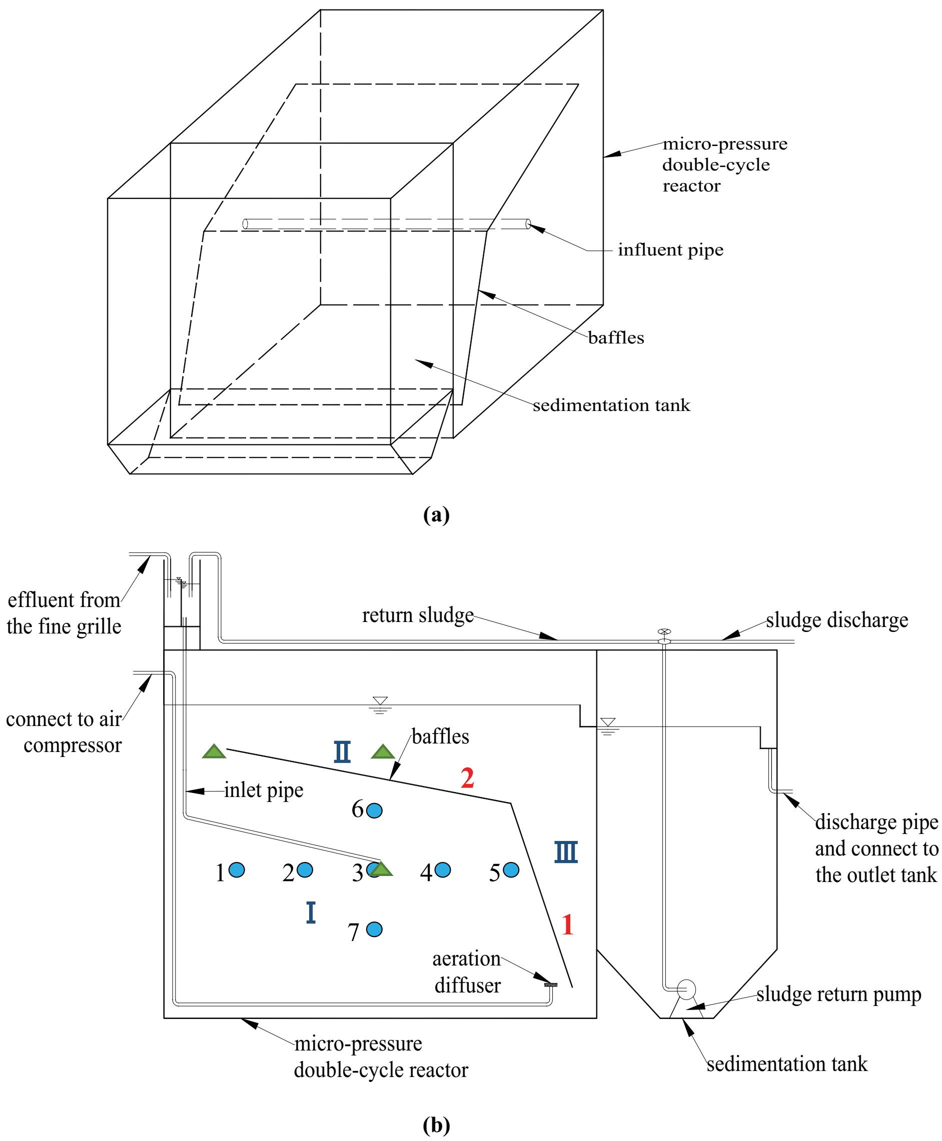


Fig. 3. (a) Three-dimensional schematic diagram of pilot test device and (b) schematic diagram of technological process and distribution of test points of pilot test device.

Note:

- Sampling point 3 of the activated sludge sample was at the center of the MPDR, the points 1, 2, 3, 4, and 5 were on the same horizontal straight line, and the interval was 1,000 mm; the points 3, 6, and 7 were on the same vertical straight line, and the interval was 1,000 mm.
- Point marked by the green triangle in the figure was the DO monitoring points. The center point of area I (monitoring point 1) was the same as the sampling point 3 of the sludge sample. The other two monitoring points were located on the same cross-section as this point. The exit point of area I (monitoring point 2) was flush with the end of baffle 2, 800 mm from the side-wall; the center point of area II (monitoring point 3) was 800 mm from the horizontal plane.

2 d, and various operating indicators were recorded at the same time. Temperature, DO and pH were monitored by WTW Multi 340i meter with DO and pH probes (Multi340i, WTW, Germany). Chemical oxygen demand (COD) was measured with a COD quick-analysis apparatus (5B-1, Lianhua Technology Co., Ltd., China). SS, total nitrogen (TN), NH_4^+–N, total phosphorus (TP) and mixed liquor suspended solids (MLSS) were analyzed according to standard methods [12].

2.4.2. DNA extraction and polymerase chain reaction amplification method

During the stable operation of the pilot test device, the activated sludge samples at internal points (as shown in Fig. 3b) were collected and analyzed for bacterial structure. According to the manufacturer's instructions, E.Z.N.A™ Mag-Bind Soil DNA Kit (OMEGA) was used for total genomic DNA extraction. The integrity of DNA was

Table 1
Characteristic of the influent quality in pilot test

Index	Range	Average
Chemical oxygen demand (mg/L)	111.3~2,040	755.16
Total nitrogen (mg/L)	14.31~40.97	25.34
NH_4^+–N (mg/L)	5.33~15.15	12.78
Total phosphorus (mg/L)	1.89~13.12	4.82
Suspended solids (mg/L)	123~3,472	1131
T (°C)	6.9~16.0	10.5

analyzed through the agarose gel method (gel imaging system from UPV, USA).

Qubit3.0 DNA testing kits (Q10212, Life) were used in the first round of polymerase chain reaction (PCR) amplification to determine if the PCR reaction should join the DNA. Universal primers 341F: CCCTACACGACGCTCTTCCGATCTG (bar code) CCTACGGGNGGCWGCAG and 805R (GACTGGA GTTCCTTGGCACCCGAGAATTCCAGACTACHVGGG ATCTAATCC) were utilized to amplify V3-V4 (Miseq sequencing platform). PCR primers compatible (Illumina) were introduced for the second round of PCR amplification [13].

3. Results and discussion

3.1. Laboratory fluid state simulation test results

Figs. 4a and b are the liquid velocity distribution contour map and liquid velocity vector distribution diagram of the numerical simulation of the flow field of the MPDR model when the aeration amount was 0.2 m^3/h. The flow of the liquid phase in the model area I shows a cyclic flow, and the gas rose along with the baffles, pushed the liquid to form a circular cyclic motion, and the peripheral circulation speed was fast, and it gradually decreased inward. The center flow rate was close to zero. Area II formed a circulation flow opposite to the circulation direction of area I, and the circulation velocity was lower than that of area I. Similar to the area I circulation, area II circulation flow also gradually decreased from outside to inside. Flow velocity in most zones of area III was close to zero, which indicated that under the experimental conditions, the reactor could form a good sedimentation zone in area III. Also, under the combined action of its gravity and the suction of aeration, the flow velocity at the bottom of area III relatively increased, so that the liquid in this area could flow back to area I. The numerical simulation of the flow field showed that the MPDR could obtain the expected flow pattern distribution under reasonable aeration conditions. To further confirm the simulation effect, the clear water verification test was carried out.

Figs. 4c–f are photos of the state of pink ink diffusion at the 7, 12, 25, and 35 s of the clear water verification test. In the initial stage of pink ink entered the test model, the pink ink moved along the baffle plates 1 and 2 with the aeration driven, and the diffusion range was small. As the liquid phase circulation in the reactor progressed gradually, the pink ink gradually diffused to the entire area I. At that time, part of the pink ink moved to area II with the bubbles. Due to the slower flow rate, the pink color diffused in this area later than the area I, compared the numerical simulation of the flow field with the clear water verification pictures, it could be seen that the baffles effectively guided the flow direction of the bubbles, and the liquid formed two circulation areas in the reactor. The circulation flow with decreased velocity from outside to inside has laid a structural foundation for the actual hydraulic conditions distribution, DO distribution and sludge concentration distribution, which had been confirmed in MPSR research [8]. The test proved that the expected flow pattern distribution of the MPDR design could be achieved under an appropriate aeration amount.

3.2. Sewage treatment effect of pilot plant

The SS removal effect of the MPDR pilot test device is shown in Fig. 5a. The concentration of influent SS fluctuated sharply. The range of influent SS concentration was 123~3,472 mg/L, the range of effluent SS concentration was 10~96 mg/L, and the average effluent concentration of SS was 48.60 mg/L. The removal rate of SS reached 86.57%. Combined with the change of inlet water temperature in Fig. 5f, the change of the concentration of influent SS could be explained by climate change. The main reason for the rapid increase in the SS concentration of the influent was that during the gradual increase in temperature between winter and spring and the high temperature in summer, the snow melted and rainfall in these two periods formed runoff, thereby carrying sediment into the sewage treatment plant. The unhardened ground and building construction in the high-tech development area also provided conditions for this. The high concentration of the influent SS not only impacted the biological aeration tank but also caused the sedimentation tank to be seriously overloaded. It could be seen from the data monitoring results that, except for the number of days when the influent SS exceed 3,000 mg/L, the SS concentration of the effluent from the pilot test device was less than 50 mg/L. The low SS concentration of the effluent could reduce the load of the subsequent treatment process and improved the operational efficiency of the urban sewage treatment plant. The unique design structure of the MPDR provided the basis for the high removal efficiency of SS. Compared with the traditional aeration tank, the MPDR was partitioned by the baffles, formed a unique sedimentation zone in the aeration tank. When the SS concentration in the influent was high, the sedimentation zone assisted the sedimentation tank to increase the volume of the sedimentation area of the system and prolonged the separation time of the activated sludge and water, thereby trapping more SS to improve the SS removal rate. The test results proved that the pilot test device had a good SS removal effect and had a strong ability to resist the impact of high-concentration influent SS.

The COD removal effect of the MPDR pilot test device is shown in Fig. 5b. Fluctuations in the COD concentration of the influent were also severe. The COD of the influent varied from 111.30 to 2,040.00 mg/L, the COD concentration of the effluent varied from 15.05 to 47.82 mg/L, and the average effluent concentration was 26.26 mg/L. The average removal rate of COD was 92.61%. Comparing the concentration fluctuations of influent COD and influent SS, it was found that there was a strong correlation between the two. When the SS concentration in the influent rose sharply, the COD

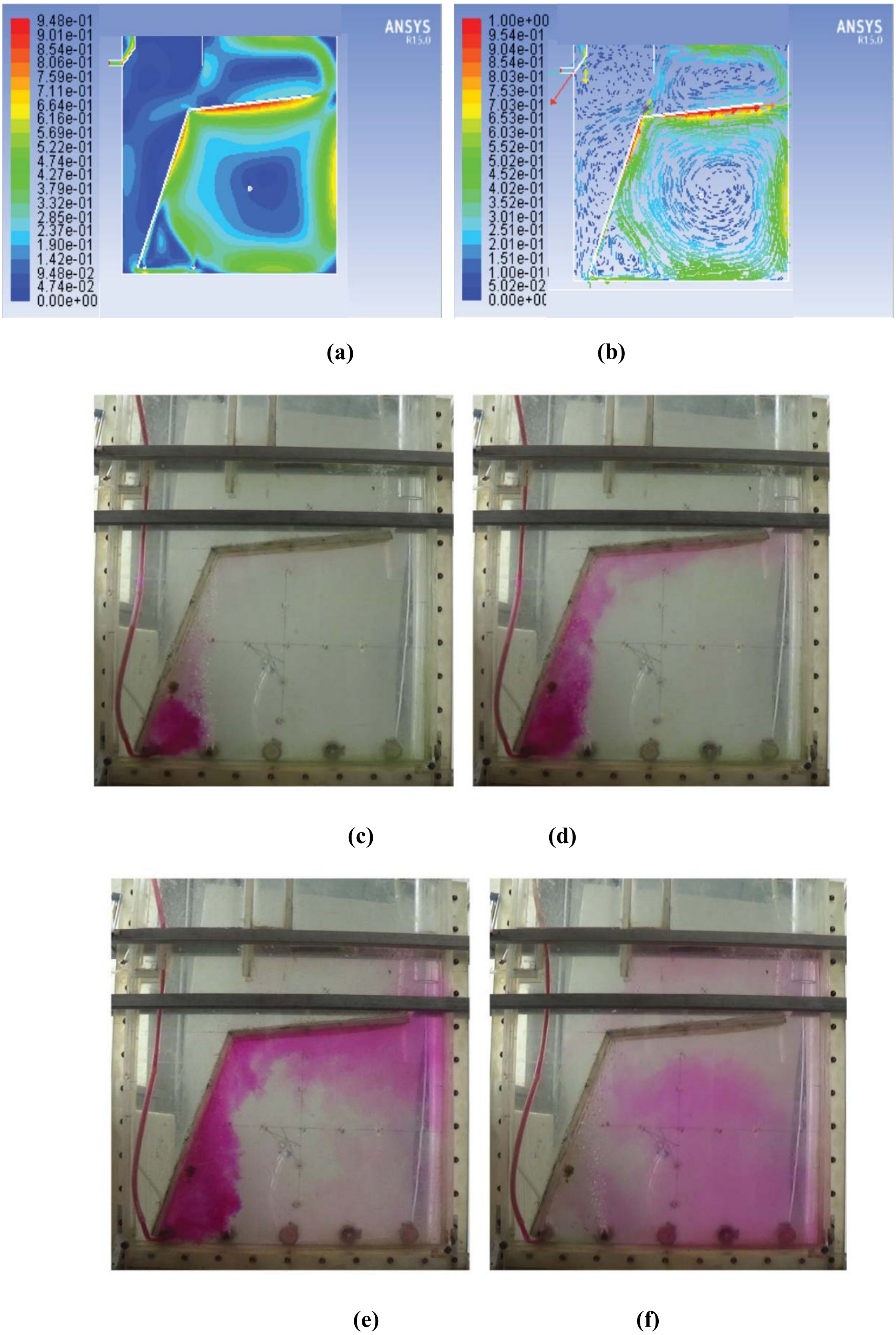


Fig. 4. (a) Liquid velocity distribution contour graph, (b) liquid velocity vector distribution graph, (c) ink diffusion model photo after 7 s, (d) ink diffusion model photo after 12 s, (e) ink diffusion model photo after 25 s, and (f) ink diffusion model photo after 35 s.

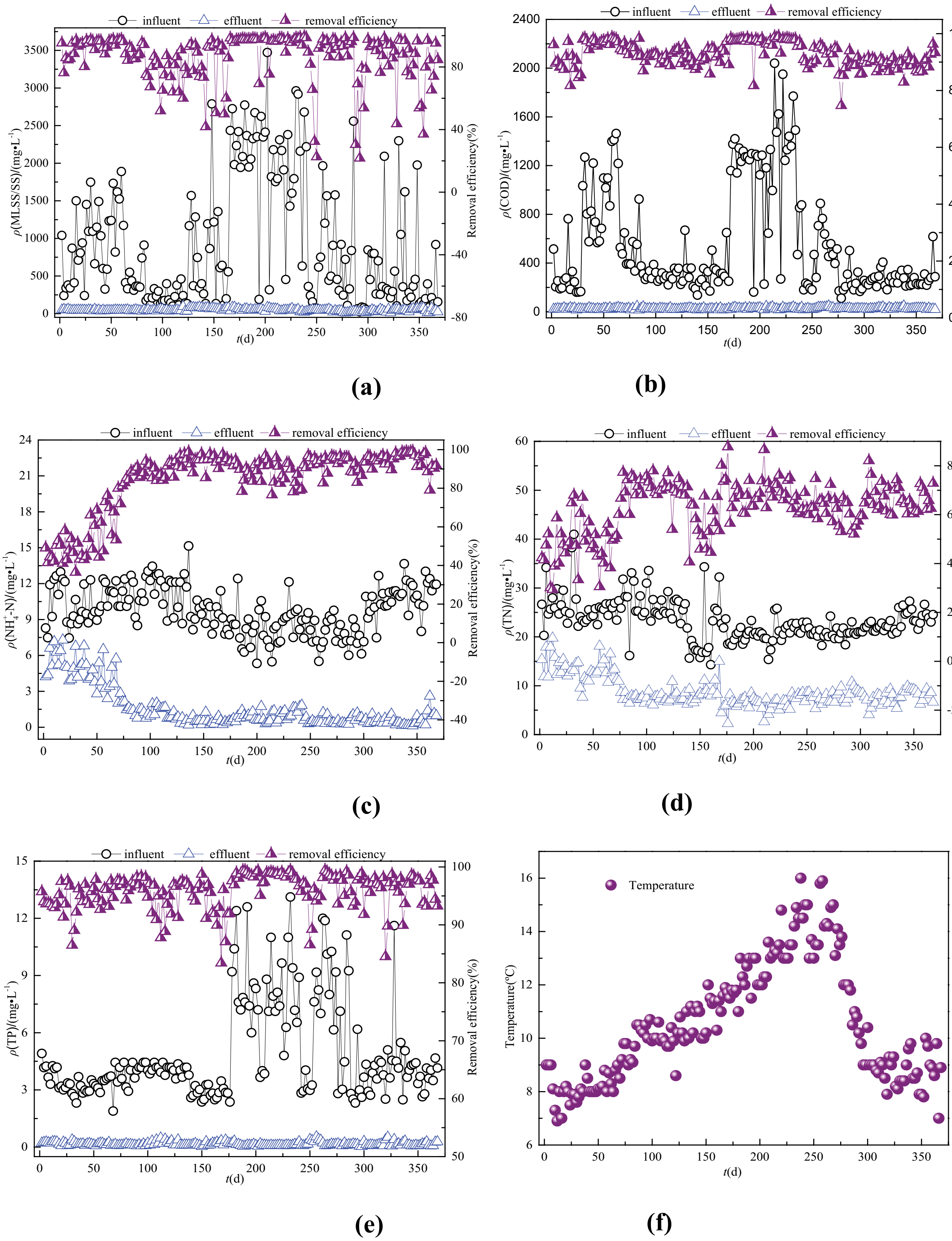


Fig. 5. (a) SS removal effect of pilot test device, (b) COD removal effect of pilot test device, (c) NH_4^+–N removal effect of pilot test device, (d) TN removal effect of the pilot test device, (e) TP removal effect of the pilot test device, and (f) influent temperature change during the test.

concentration in the influent also increased. But unlike SS, the MPDR pilot test device had always been very effective in removing COD. The COD concentration of the effluent during the entire test period was lower than the 50.00 mg/L required by Class A standard of the comprehensive discharge standard of Chinese urban sewage treatment plants [14]. The good removal effect of COD was related to the high-efficiency removal of SS. The efficient use of organic matter in the pilot test device was another reason. Sewage entered from the center of the pilot test device, and first entered the circulation flow center of area I. Because the flow rate of the mixed liquid in the area was slow and in anoxic state, the residence time of sewage was long, and the organic matter in it was more able to use for phosphorus release and denitrification. When sewage was pushed from the central zone of area I to the aerobic zone around area I, some organic matter would be further oxidized. Driven by the flow of mixed liquid, sewage flowed from area I to area II. The resulted of DO test indicated that the center of the area II was in anoxic state and the DO was less than 0.50 mg/L. Because of the wide range of available carbon sources for denitrification [15], some refractory organic matter could be further utilized by denitrifying bacteria in this area, thereby further reducing the COD concentration in the effluent.

The removal effects of NH_4^+–N and TN in the MPDR pilot test device are shown in Figs. 5c and d. The fluctuation law of influent nitrogen concentration was different from other water quality indicators. Compared with the sharp fluctuations of SS and COD, the changed concentration of NH_4^+–N and TN in the influent during the test period were relatively flat. This was related to the fact that most of the sewage received by the pilot test device came from industrial parks and less domestic sewage was received. During the test period, the influent concentration of NH_4^+–N and TN fluctuated within the range of 5.33~15.15 mg/L and 14.31~40.97 mg/L respectively, and the average concentration of the effluent NH_4^+–N and TN during stable operation was 0.57 and 8.72 mg/L respectively. It can be seen from Figs. 5c and d that the denitrification effect of the pilot test device was not ideal within 100 d after the start of the test. During the period, the average effluent concentration of NH_4^+–N and TN reached 4.93 and 13.48 mg/L, and the average removal rates were only 51.82% and 47.74%. The main reason for the low nitrogen removal efficiency during this period was that the sludge inoculation into the pilot test device required a period of adaptation, while the inlet water temperature was low during this period. Studies had shown that the removal efficiency of ammonia was stable at about 90% at 15°C in the activated sludge treatment process, but dropped to about 20% at 10°C and the process failed at 5°C [16,17]. The low reproduction rate of nitrifying bacteria led to the poor nitrification effect of the pilot test device for a long time. After the nitrification process was suppressed, denitrification could not proceed, resulting in a lower TN removal rate. After the temperature of the influent water gradually increased and rose above 10°C, the nitrification effect of the system was rapidly improved. After that, the NH_4^+–N concentration in the effluent was below 1.00 mg/L, and the subsequent temperature drop again did not affect the nitrification process of the system. After the system nitrification rate was increased, the TN removal efficiency of the system was also rapidly increased. The test results showed that the main limited step for nitrogen removal in the pilot test device was nitrification. When the sludge was inoculated under low-temperature conditions, the nitrification efficiency of the pilot test device was improved slowly, and after the system nitrification efficiency was improved, the effect of low temperature on the nitrification of the system would be reduced [18].

The good effect of nitrogen removal during the stable operation of the pilot test device was also related to the structure of the MPDR. The influent first entered the central area of area I, which was anoxic. Organic matter preferentially participated in denitrification to remove nitrate–nitrogen in the influent and return sludge. Besides, part of the organic matter was used for anaerobic phosphorus release. Therefore, there was less organic matter entered the aerobic zone around area I, which could inhibit the growth of heterotrophic bacteria, promoted the propagation of nitrifying bacteria, and ultimately improved the nitrification efficiency [19]. The MPDR also has an anoxic zone in area II, which will further remove TN. Through different DO environments and hydraulic conditions, MPDR realized the functional division of nitrification and denitrification in area I, which improved the system's nitrogen removal efficiency. The two-stage denitrification in area I and area II also helped the removal of nitrogen in the system.

The TP removal effect of the MPDR pilot test device is shown in Fig. 5e. The influent TP concentration also fluctuated sharply. Influent TP concentration varied from 1.89 to 13.12 mg/L, effluent TP concentration varied from 0.03 to 0.54 mg/L, and average effluent concentration was 0.17 mg/L. The average removal rate of TP reached 95.70%. During the test period, the removal rate of TP in the pilot test device was high, and the TP effluent concentration was less than 0.50 mg/L. The change of TP concentration in the effluent was related to the effluent SS. In the one-year experiment, the number of days when the TP effluent concentration exceeded 0.50 mg/L was only 3 d, and the effluent SS concentration exceeded 50 mg/L on that day. Besides, the unique design of the MPDR also facilitated the efficient removal of TP. The sewage first entered the anoxic/anaerobic zone of the system. The organic matter contained in the influent water could make the system fully release phosphorus, and then entered the aerobic zone of the system for phosphorus absorption. When the sewage was pushed into areas II and III with low DO concentration, the phosphorus was not released again because of the low organic content and the presence of nitrate nitrogen.

Although the influent water quality of the sewage treatment plant changed from moment to moment, the violent fluctuation would inevitably affect the microorganisms that participate in the biochemical reaction, resulting in poor effluent water quality. During the test, the MPDR pilot test device had a satisfactory treatment effect on sewage. Excepted for the SS effluent concentration occasionally exceeding the standard, the average effluent concentration of COD, NH_4^+–N, TN, TP was lower than the class A standard of the comprehensive discharge standard of Chinese urban sewage treatment plants. The test result proved that under the premise of severe fluctuation of the influent water quality, the MPDR could stably remove organic matter, nitrogen, phosphorus and other pollutants in the sewage, and has a strong impact on load resistance. MPDR could better solve the practical problems caused by high SS concentration and low feedwater temperature, and could provide a new way for the upgrading of urban sewage treatment plants.

3.3. Dissolved oxygen and sludge concentration during the test

The changed of average activated sludge concentration and DO in the pilot test device during the test are shown in Fig. 6. It is known from Fig. 6a that the sludge concentration in the pilot test device during the test period was higher than that of the general biochemical tank, and the average concentration reached 8,978 mg/L. It was caused by the high SS concentration in the influent and the sludge retention by the MPDR. During the experiment, the average sludge concentration in the reactor ranged from 3,740 to 17,370 mg/L. Comparing the change in the concentration of the influent SS, it could be found that the influent SS was the direct cause of the severe fluctuation of the MLSS. In the design and operation of the pilot test device, the sludge age was set to 30 d, and then the sludge discharge volume was calculated by multiplying the average MLSS in the reactor by 1/30 of the effective volume of the reactor, and then converted to the volume in terms of the concentration of the returned sludge. In actual operation, when the SS concentration of the influent exceeded 500 mg/L, the amount of sludge discharged increased the SS carried into the system by the influent. Specifically, the SS concentration of the influent was multiplied by the influent volume of the day, and then converted to the volume recorded in terms of the concentration of the returned sludge, which was the increased sludge volume. In this way, the reactor volume was prevented from being occupied by inorganic substances, and the HRT of the influent was guaranteed.

Higher sludge concentration could promote the denitrification and dephosphorization of the biochemical system. On the one hand, high sludge concentration increased the number of denitrifying and dephosphorizing functional flora and improved the efficiency of denitrifying and dephosphorizing in the system. On the other hand, high sludge concentration could improve the system the anti-shock load capacity, especially under high-load shock, the higher biomass of the system could alleviate the shock load while efficiently removing pollutants and ensuring the quality of the effluent, which was particularly important for this test. Similarly, high concentration of MLSS also brought adverse effects. Firstly, it would increase the aeration energy consumption of the system. Secondly, it would increase the system's anoxic area, thus affecting the treatment effect. To verify the aeration operation effect of the MPDR under high MLSS, the distribution of DO in the reactor was studied.

To verify the effect of the aeration operation of the pilot test device under high MLSS, the three outlets of area I (monitoring point 1), the area II circulation center (monitoring point 2) and the area I circulation center (monitoring point 3) were selected to detect the dissolved oxygen. DO detected results are shown in Fig. 6b. The DO fluctuation at monitoring point 1 was greater than the other two points, and its DO value was the highest. Monitoring point 1 was located in one of the area where the action of bubbles and the mixed liquid was most intense. The three-phase flow of gas, liquid and solid was turbulent, so the DO value fluctuated sharply here. The DO values at monitoring points 2 and 3 were relatively stable, and the DO values at monitoring point 2 were lower than that at monitoring point 3. During the test, the average DO values at monitoring points 1, 2, and 3 were 1.60, 0.23, and 0.43 mg/L, respectively. From the DO test results, it could be seen that the change in DO value in the pilot test device during the test period was less affected by the fluctuations in the influent quality and the influent temperature. The test results showed that under the experimental conditions, the reaction device could stably

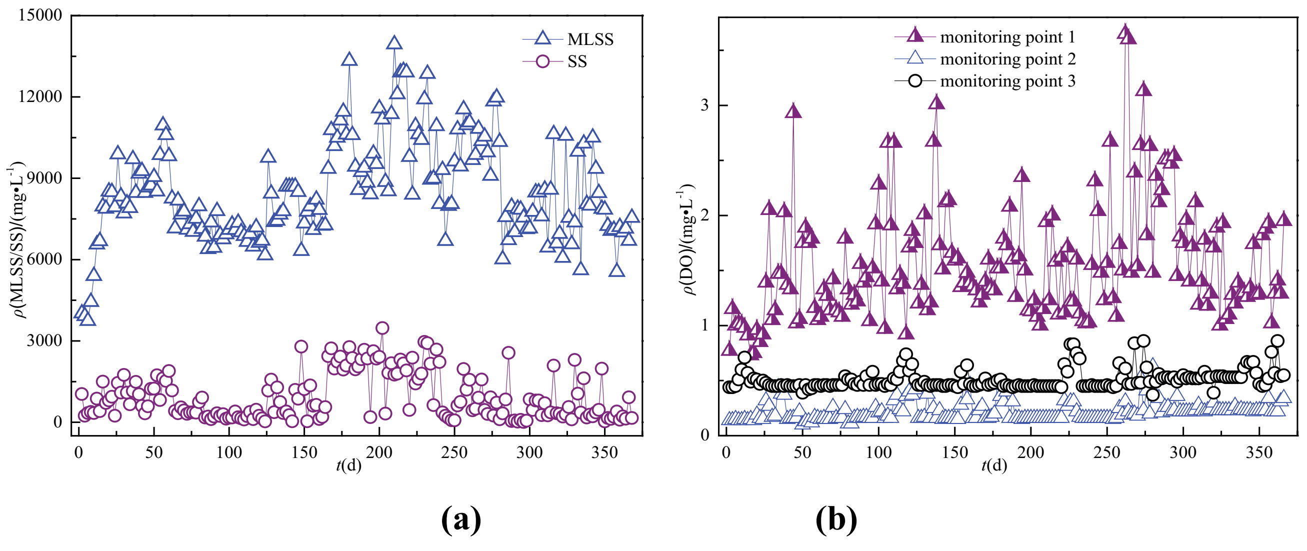


Fig. 6. (a) Changes in average MLSS concentration in the reactor and changes in SS concentration in the influent during the test and (b) changes in DO during the test period at three DO monitoring points.

form an anoxic zone in the center of area I, while forming an aerobic zone in the surrounding area I. With the accumulation of sludge in the center of area II, a stable anoxic zone was gradually formed. The distribution of DO in the pilot test device provided important basic conditions for the removal of pollutants. The stable maintenance of DO in each area provided a guarantee for the effluent quality of the pilot test device.

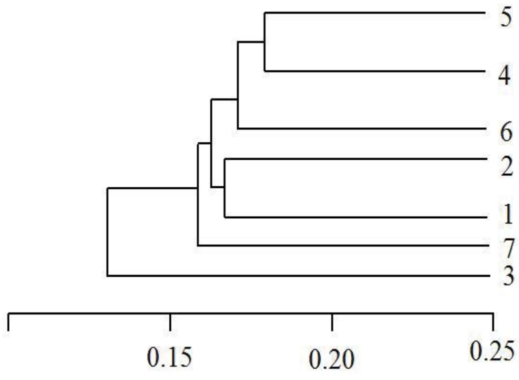
3.4. Microbial community analysis in the pilot test device

After the operation of the pilot test device was stable, taken sludge samples from 1, 2, 3, 4, 5, 6, 7 of the internal sampling points (shown in Fig. 3b) of the test device. In this study, to investigate the distribution of the main functional flora in the pilot test device, the main reaction area I was selected for the test and the sampling points of the sludge samples were all distributed in this area. Bio-community analysis of the sludge samples taken, the results are shown in Table 2 and Fig. 7. It is known from Tab.2 that the detection coverage of the seven sludge samples all reached more than 0.96, which showed that the high-throughput sequencing results of the samples were in good agreement with the real conditions of the samples. The Shannon index and the ACE estimator index of the samples have the same change law, combined with the analysis of the Operational Taxonomic Units (OTU) number of each sample showed that there was a certain difference in the distribution of the activated sludge biological community in area I. The UPGMA (Unweighted Pair Group Method using Arithmetic Average) algorithm was used to perform cluster analysis on the similarity of seven sample bacterial communities. The results are shown in Fig. 7a. Samples 1, 2 and samples 4, 5 have high similarity, while sample 3 has the lowest similarity with other samples. Combined with the sampling point distribution, it was found that the similarity between the sample floras was closely related to the external environment where the sample sampling point was located. The sludge mixture in area I of the main reactor exhibited a periodic annular push flow motion. Due to the different circulation velocities, the stratification phenomenon gradually appeared in the circulation flow in area I. Microbiological testing results showed that the closer the flow pattern at the sample collection point, the higher similarity of the sample flora. A sampling point 3 in the center of the reactor, the sewage entered the reaction device, and the hydraulic disturbance in that point was small, and the flow velocity was slow, so the community distribution was more complicated and the difference from other samples was large. The above analysis showed that during the operation of the pilot test device, the structure of the microbial population had undergone complex succession change and there was a large spatial difference.

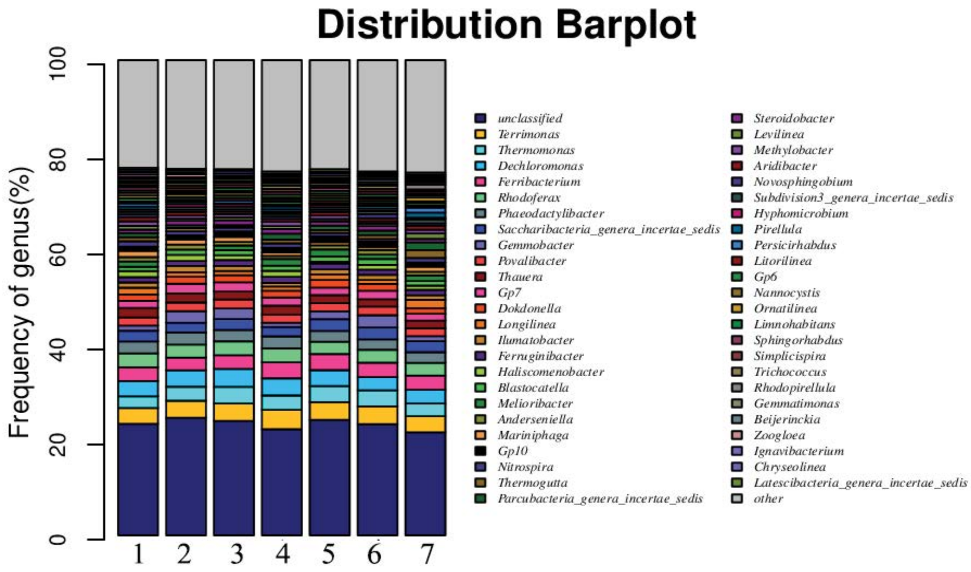
Fig. 7b shows the distribution of all sample community structures at the genus level. The figure listed the distribution of the top 50 species classifications with the highest abundance ratio in the sample species classifications. Among them, genera with significant functional characteristics include *Decachloromonas*, *Thauera*, *Thermomonas*, *Nitrospira*. These were the bacteria that participate in the nitrogen and phosphorus removal function in the biological treatment of sewage. *Thauera* and *Thermomonas* were bacteria with denitrification function in the biological treatment of sewage [20,21]. *Dechloromonas* was known as denitrification and phosphorus removal bacteria [22]. *Nitrospira* could oxidize NO_2^- to NO_3^-, which was a typical nitrification function of bacteria [23]. It could be seen that the contents of *Dechloromonas* in each sample point were 3.61%, 3.35%, 3.78%, 3.19%, 3.48%, 2.77%, and 2.89%, and the distribution of *Dechloromonas* in the whole area I was relatively rich. It could be known from the analysis of the microbial community that *Dechloromonas* was the main phosphorus removal bacteria in the pilot test device, so denitrifying phosphorus removal was one of the main phosphorus removal ways of the system. The relatively abundant content of *Dechloromonas* might be related to the relatively low aeration of the system and the large area of anoxic. The rich content of *Dechloromonas* further confirmed the results of nitrogen and phosphorus removal in the pilot test device, and its presence also improved the system's utilization of carbon sources. Unlike the distribution of *Dechloromonas*, the distribution of *Nitrospira* in area I was relatively uneven. The contented of *Nitrospira* at each sample point were 0.24%, 0.12%, 0.03%, 0.94%, 1.15%, 0.27%, 0.17%. According to the distribution of *Nitrospira* in area I, *Nitrospira* was sensitive to the DO content in the environment, with high content in the area with high DO, and a large decreased in the area with low DO. The aggregation of *Nitrospira* was a concentrated reflection of the advantages of MPDR. MPDR formed different DO environments and hydraulic conditions inside the reactor, caused microorganisms with different functions to accumulate in different areas of the reactor, avoided competition between bacterial groups, improved the space utilization of the reactor, and thus promoting the reactor of pollutant removal efficiency.

Table 2
Abundance and diversity of 16S rRNA sequences in activated sludge samples

Sample ID	Seq. num.	OTU num.	Shannon index	ACE index	Chao1 index	Coverage	Simpson
1	40,685	2,810	6.21	5,462.33	4,604.92	0.97	5.3e-03
2	35,463	2,748	6.22	5,718.23	4,759.68	0.97	5.1e-03
3	59,361	3,522	6.25	7,675.63	6,172.06	0.97	5.3e-03
4	32,084	2,689	6.18	5,870.53	4,645.51	0.96	6.0e-03
5	36,895	2,651	6.14	5,448.81	4,617.9	0.97	5.7e-03
6	26,930	2,315	6.11	4,989.52	3,969.11	0.96	5.8e-03
7	52,283	3,197	6.26	6,649.58	5,320.90	0.97	5.1e-03



(a)



(b)

Fig. 7. (a) Clustering diagram of all samples at the level of genus and (b) distribution of community structure of all samples at the level of genus.

4. Conclusions

In the study, referred to the working principle of the MPSR, the traditional biological aeration tank was transformed, and a MPDR suitable for the upgrading of the sewage treatment plant was designed. The simulation test and the pilot test research of urban sewage treatment have drawn the following main conclusions.

- The flow state simulation test of the MPDR showed that under the appropriate aeration amount, the MPDR could form a circulation flow that gradually decreased from the outside to the inside in the areas I and II. The presence of two circulating streams enabled the circulation of the material in the reactor.
- The pilot test of the urban sewage treatment of the MPDR showed that the MPDR could realize the efficient removal of SS, COD, NH_4^+–N, TN, TP under the conditions of drastic change in water quality and low water temperature. The test proved that MPDR could better solve the practical problems caused by high SS concentration and low influent temperature, and could be used as a new way for the upgrading of urban sewage treatment plants.
- Analysis of the types of microorganisms showed that the main phosphorus removal system of the system was denitrifying phosphorus removal. There was a big difference in the spatial distribution of microorganisms in the reactor. The distribution of microorganisms with different functions improved the space utilization of the reactor.

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