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Full scale application of combined SBF – AS process for municipal wastewater treatment in small towns and cities in China

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Abstract: The combined submerged biofilm (SBF)-activated sludge (AS) process for treatment of municipal wastewater in a small city in China is described in this paper. The process exhibited high removal efficiencies for carbonaceous substances, nitrogen and phosphorus which mainly took place in the combined SBF-AS bioreactor. The SBF-AS bioreactor was divided into pre-anoxic, anaerobic, anoxic and aerobic zones from inlet to outlet, in which fixed biofilm carriers were packed. Excellent performance had been obtained under normal operating conditions in more than one year of operation in Dong'e municipal WWTP, Shandong province, with mean removal efficiencies of BOD_5 93.4%, COD 88%, SS 92%, NH_4^+ – N 82.1%, TP 75% and TN 66.7%, and quite high effluent quality such as BOD_5 6 to 10 mg/L, COD 20 to 40 mg/L, SS 5 to 10 mg/L, TN 10 to 20 mg/L, NH_4^+ – N 4 to 8 mg/L and TP 0.6 to 1.0 mg/L. The effluent was reused multi-purposely, such as toilet flushing, green belt watering and artificial lake pounding. Simultaneous nitrification and denitrification took place due to the DO gradient in biofilm in aerobic zone of the SBF-AS bioreactor, which made TN removal efficiency improved remarkably in system. Some activated sludge was returned from final clarifiers to the bioreactor for phosphorus removal. The process had the advantages of low investment and low operational/maintenance (O/M) costs, low sludge yield and was preferably employed in small towns and cities.

Key words: wastewater treatment plant (WWTP) in small cities and towns; combined submerged biofilm-activated sludge (SBF-AS) process; simultaneous nitrification and denitrification (SND); DO gradient; phosphorus removal

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Facing a serious water pollution situation, China has been increasing the investment largely in the construction of municipal WWTPs, but most of them are built in big cities. With the development of numerous small communities between urban and rural areas, wastewater drainage is increasing greatly. However, the percentage of wastewater treatment in those small communities or towns at present is less than 5%. In addition, the discharge of untreated wastewater from those small towns has become main pollution sources to the water environment in some areas, and hence it is necessary to construct and put into operation more WWTPs in small towns or communities. In comparison with big cities, the sewage plants in small cities and towns are characterized by small treatment capacity, sharp variation of daily and hourly sewage flow and quality, high industrial wastewater concentration and flow, shortage of investment and low technical and management level. Therefore, the treatment process to be employed in a WWTP in a small city or town should be cost-effective, energy saving and easy to operate and maintain.

The combined submerged biofilm-activated sludge process (SBF-AS) is a highly efficient wastewater treatment technology, which appears with the development of a new type of biofilm carriers in the 1980s[1-5]. The suspended microbial community (activated sludge flocs) coexists with attached growth biomass (biofilm) in a bioreactor, in which the biofilm carriers are packed. Various kinds or forms of substances and energy transfers from biofilm inside to outside and from biofilm surface to the waterfilm and bulk water and vice versa take place by the functions of food chains. These food chains consist of organic substrate, bacteria, fungi, algae, protozoa and metazoa formed in the biofilm attached to the carrier surface and their environment consists of aerobic, anoxic and anaerobic zones, while wastewater achieves purification as well.

Meanwhile, the advantages of this process, such as low investment and operational cost, easy to operate and maintain, low sludge yield and high load resistance, made it more feasible to apply in small towns and cities in China. The Municipal WWTP (MWWTP) in Dong'e County low reaches of Yellow River, in the west of Shandong Province, employed the combined

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SBF-AS process developed by the authors and had achieved high performance in more than one year's operation. The paper describes the design and operational performance of the MWWTP using the combined SBF-AS process.

1 Materials and Methods

1.1 Influent and Effluent Characterization

Dong'e Municipal WWTP, in the north part of Dong'e country, was built in November 2001 and put into operation in October, 2002. The plant was designed for removal of organic matter (COD, BOD_5), nitrogen (N) and phosphorus (P) from the mixed domestic and industrial wastewater of Dong'e country town with the capacity of 40 000 m^3/d. The COD, BOD_5, N and P removal are mainly accomplished in a biological system which consists of two parallel combined SBF-AS bioreactors.

In this county town, the ratio of industrial wastewater is high and the percentage reaches 50% with the fast development of industry in the small city, so that the influent quality and quantity varies sharply with the change of factory production. The values of raw water quality parameters adopted in design and the actual analytical data in operation are shown in Tab. 1.

Because the effluents from some factories were not effectively controlled in the beginning operation periods, the maximum value of influent parameters of the WWTP obtained in operation was much higher than the respective design values, except TP concentration. In order to guarantee normal operational performance, some industrial wastewaters which did not meet the drainage standard were not allowed to flow into this WWTP, and since then the actual concentration range is generally lower than that used in design.

Tab.1 Design and recorded data of Dong'e Municipal WWTP

Parameters	Unit	Design values in 2001	Recorded value range (mean value) in 2001 - 2002
ρ(COD)	mg/L	400	105.3 - 865.6 (327.9)
$\rho(BOD_5)$	mg/L	150	69.2 - 381.3 (160.6)
ρ(TP)	mg/L	5	1.1 - 14.4 (3.7)
ρ(TSS)	mg/L	200	40 - 645.5 (161.0)
$\rho(NH_4^+ - N)$	mg/L	30	11.2 - 68.3 (34.3)
ρ(TN)	mg/L	45	38 - 72.5 (49.2)
$\rho(NO_3^- - N)$	mg/L		0.02 - 0.5 (0.08)
$\rho(NO_2^- - N)$	mg/L		0.07 - 2.6 (0.6)
pH			6.9 - 9.4 (7.8)

The final effluent of the WWTP should meet the national integrated wastewater discharge standard (B81918 - 2002) which in winter should meet 1B standard such as $\rho(COD) \leqslant 60$ mg/L, $\rho(BOD_5) \leqslant 20$ mg/L, $\rho(TP) \leqslant 1.5$ mg/L, $\rho(NH_4^+ - N) \leqslant 8(15)$ mg/L, $\rho(SS) \leqslant 20$ mg/L and $\rho(TN) \leqslant 20$ mg/L, and in other seasons meets 1A standard such as $\rho(COD) \leqslant 50$ mg/L, $\rho(BOD_5) \leqslant 10$ mg/L, $\rho(TP) \leqslant 1.0$ mg/L, $\rho(NH_4^+ - N) \leqslant 5(8)$ mg/L, $\rho(SS) \leqslant 10$ mg/L and $\rho(TN) \leqslant 15$ mg/L.

1.2 Flowchart of Combined SBF - AS Process

As shown in Fig. 1, the treatment system consisted of coarse screens, pumping station, fine screens and aerated grit chambers as pretreatment units, combined SBF-AS bioreactor, final clarifiers and polishing

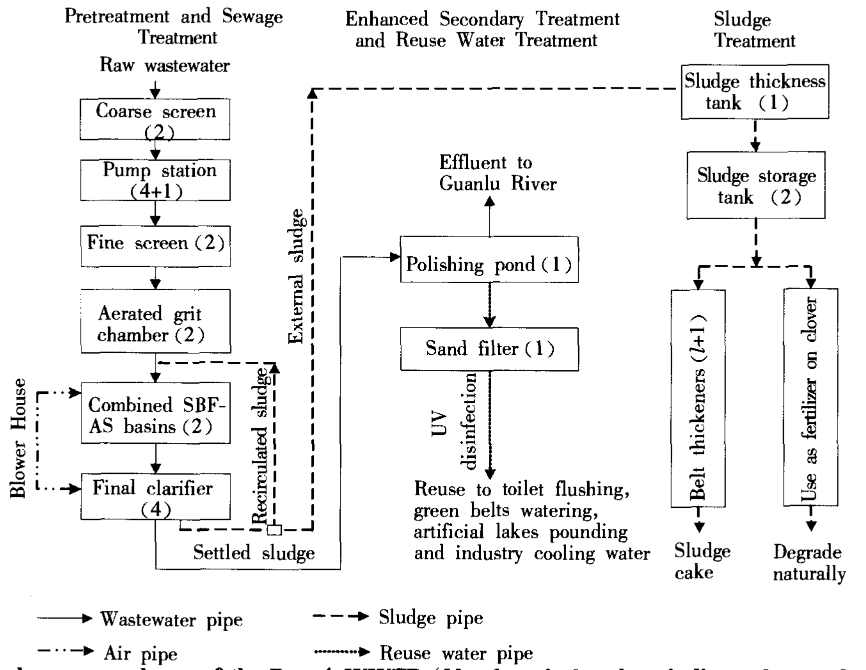
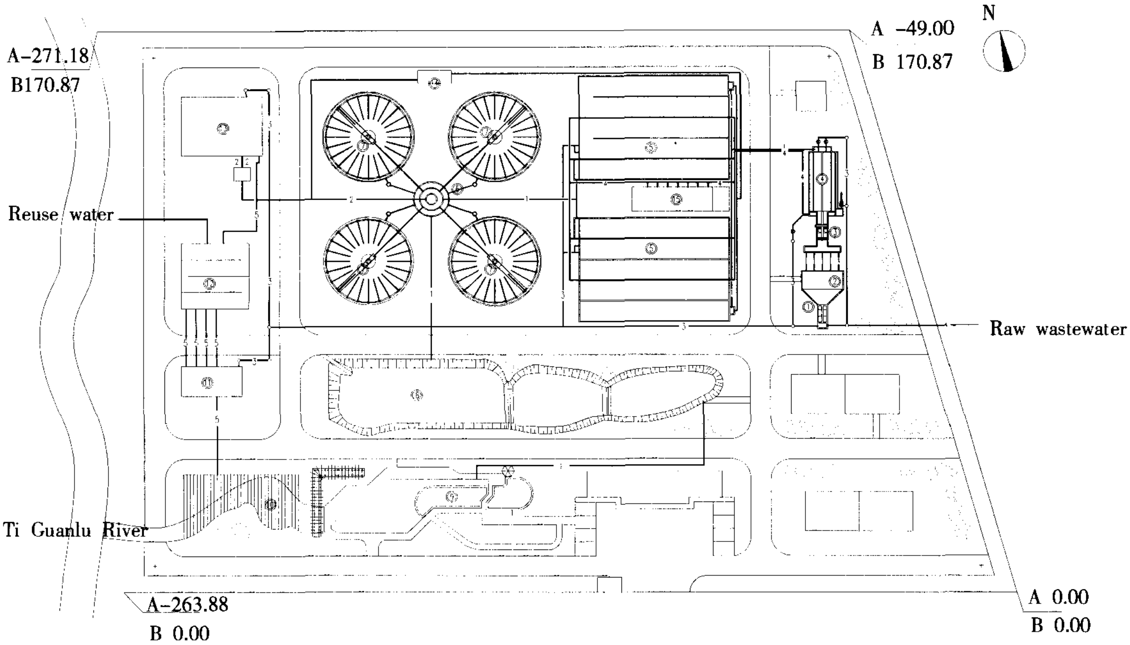


Fig.1 Simplified block process scheme of the Dongê WWTP (Numbers in brackets indicate the number of process units)

pond as wastewater treatment units, sand filter as water reclamation and reuse units, and sludge thickeners and belt press for sludge dewatering as sludge treatment units. Fig. 2 shows the layout of Dong'e Municipal WWTP.



1—Raw wastewater pipe; 2—Sludge pipe; 3—Wastewater pipe of WWTP; 4—Air pipe; 5—Reuse water pipe

Fig. 2 Layout of Dongê WWTP

The raw wastewater first flows through the coarse screens to remove the large solid wastes, then flows to the wastewater collection sump which is underground for equalizing sewage quality and quantity. The five wastewater pumps (four operating and one on standby) feed sewage from the wastewater collection sump to fine screens for small solid wastes removal, from which the effluent flows into the aerated grit chambers to remove the sand and other inorganic particles. Then the pretreated wastewater flows by gravity into the combined SBF-AS bioreactor, the key treatment unit of the whole treatment system with a dimension of 44 m × 31.8 m × 5 m ($L \times W \times H$) (single basin) and divided into five corridors which have a pre-anoxic/anaerobic zone in the first corridor and anoxic/aerobic zone in the second corridor in which DO can be adjusted according to the need of operation and aerobic zones in the last three corridors. In the combined SBF-AS bioreactor basins, the multi-surface hollow-ball form carriers made of polyethylene are packed in each corridor which allows for the coexistence of suspended activated sludge with the attached growth biofilm. The biofilm that attaches and grows on the carrier surface can absorb the organic substance in wastewater largely because of large surface area, while the organic substance is degraded. The process in which various substances transfer from biofilm inside to outside and from biofilm surface to water-film in the micro environment formed on the carriers surface is described as follows: by aeration, the oxygen is dissolved in water-film by which DO further transfers into biofilm, and supplied for microbial respiration, while organic substances transfer from bulk water flow to attached water-film on the surface of biofilm, then flow to biofilm and is degraded by bacterial metabolic activity, and the biological reaction products move from inside to outside, then water-film and bulk water flow in reverse path. As a result, the simultaneous nitrification/denitrification and biological phosphorus removal process take place, thus TN and TP can be removed partially.

To obtain high quality effluent, a total hydraulic retention time (HRT) of 7.5 h was adopted while HRT in anaerobic and aerobic zone was 1.5 – 2 h and 5 – 6 h respectively. In anaerobic, anoxic and aerobic environments, because of acidification and hydrolysis and predatory action of protozoa and metozoa in the food chains existing in biofilm, the excess sludge is reduced substantially, thus resulting in the biomass yield of only 1/10 – 1/5 that of the active sludge process[5]. In the first year's operation of this WWTP, only a small amount of sludge was discharged (about 1/10 that of activated sludge process), which was totally applied on the green belts in the yard of this WWTP as organic fertilizer.

The mixed liquid effluent of SBF-AS flowed to the final clarifiers where the sludge and water were separated. Then the effluent of final clarifiers flowed to polishing ponds 1 and 2 to be further purified. In polishing ponds, hydrophytes coexisted with fishes and waterfowls which formed an artificial ecosystem. The effluent of the polishing pond was partially reused through sand filters and disinfection as cooling water for a phosphate fertilizer factory, as well as toilet flushing, watering of the green belts and impounding of artificial landscape lake in the buildings and yard of the WWTP, and the other effluent flowed to Guanlu River directly.

2 Operational Performance and Discussion

2.1 The Start-up of Combined SBF-AS System at Low Temperature

The combined SBF-AS system started up for trial operation at low temperature (12 - 14 ℃) in winter successfully. During the start-up operation, the effluent quality of combined SBF-AS bioreactor basins was quite good with the following average data: COD 60 mg/L, BOD_5 15 mg/L, SS 20 mg/L, TP 1.0 mg/L, NH_4^+ - N 20 mg/L respectively, which all met the 1B standard of national secondary discharge class of integrated wastewater discharge standard (GB18918 - 2002), except ammonia nitrogen concentration. Because the suspended microbial communities coexisted with attached growth biofilm that exhibited much better micro-environment for microorganisms with much higher bio-activity than the former in the combined SBF-AS bioreactor, it can start up successfully at such low temperature, which the activated sludge process cannot reach. It also reflected the superiority of combined SBF-AS process to the later process.

2.2 Carbonaceous Substances Removal

From the data of 18 month's operation in Dong'e WWTP, it showed high removal efficiency for carbonaceous substances. The variation and removal of COD and BOD_5 are shown in Fig. 3.

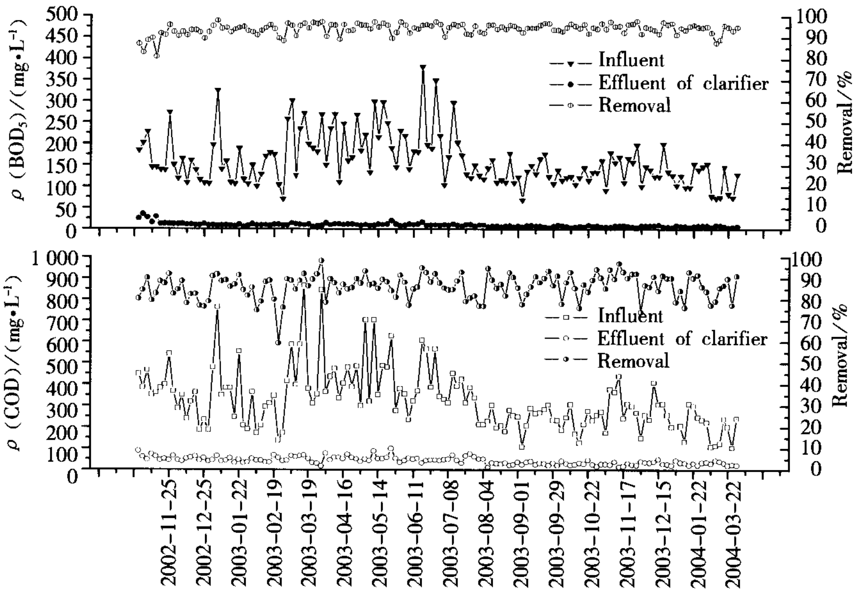


Fig. 3 Variation and removal of COD and BOD_5 of Dongé WWTP

The data points in Fig. 3 were the values from the 16th of November, 2002 to the 6th of April, 2004 and were analyzed twice a week. During the operational period of the WWTP, the influent BOD_5 varied between 69.2 - 381.3 mg/L, and COD between 105.3 - 865.6 mg/L, except in the trial run period, the average effluent BOD_5 was 8.65 mg/L, and COD 40.75 mg/L, with average removal efficiencies of BOD_5 93.8% and COD 86.2%. In February and March 2003, the influent and effluent concentration of COD and BOD_5 were much higher than design values because of the discharge of high strength distillery wastewater into the WWTP without any pretreatment in the factory.

Fig. 4 shows the BOD_5 and COD concentration variations and removal efficiencies in different corridors of the combined SBF - AS basins, the data in the table are obtained from April, 2002, during which it had the stable influent and effluent. There was a high removal efficiency for carbonaceous substances in anaerobic corridor; the COD and BOD_5 removal reached 32.7% and 30.8% respectively, and in corridors 2, 3 and 4, most of the organic substances were removed with the percentage of more than 75%. It can be concluded that the removal efficiency of the combined SBF-AS bioreactor basins is much higher than that of active sludge aeration tank because of the coexistence of high biomass of biofilm attached on the carriers with high bio-activity and suspended activated sludge flocs in the SBF-AS basins.

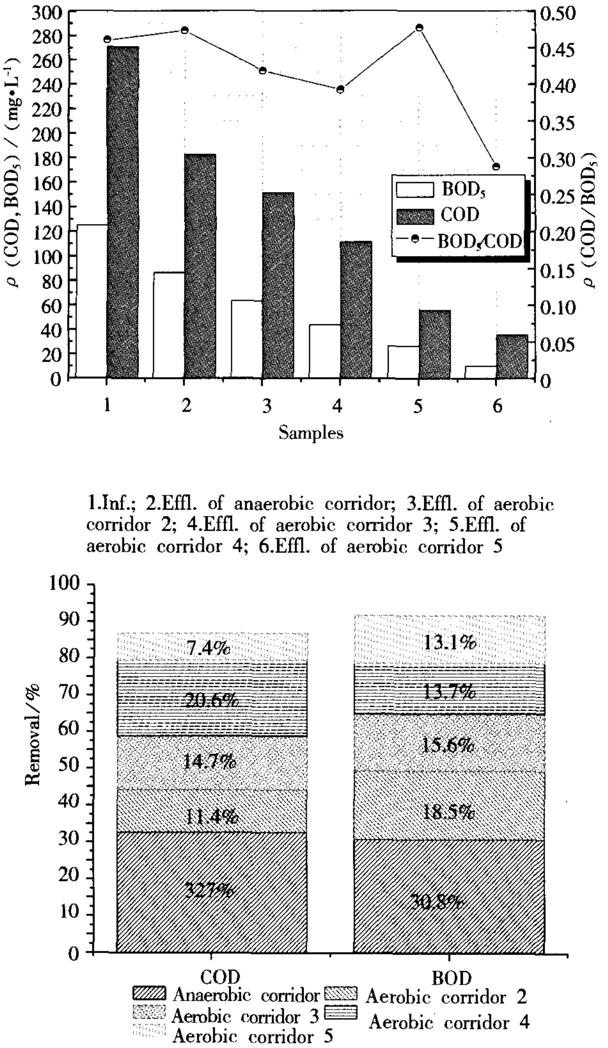


Fig. 4 Concentration variation and removal efficiency of BOD_5 and COD in different corridors of combined SBF – AS bioreactor in running period

2.3 Nitrogenous Removal

The main mechanisms of nitrogenous removal are gaseous NH_3 volatilization, metabolism of suspended and attached microbes which coexist in SBF-AS bioreactors and simultaneous nitrification and denitrification (SND) process due to existing of DO gradient in biofilm and activated sludge flocs.

2.3.1 NH_4^+ – N removal

NH_4^+ – N variation of the influent and effluent are shown in Fig. 5, from which it was found that the combined SBF – AS bioreactor system exhibited considerably high NH_4^+ – N mean removal efficiency of 82.1% in a normal operating period, during which the mean influent NH_4^+ – N concentration was 34.3 mg/L and effluent 7.3 mg/L with the rise of temperature from cold months to warm ones, thus more suitable conditions were developed for the growth of both nitrobacteria and denitrobacteria, which made the removal efficiency of NH_4^+ – N increase gradually. In comparison with the trial running period, with the increase of operation time and temperature, the attached biofilm on the carriers and the nitrobacteria/denitrobacteria in the biofilm have been increasing greatly, which created the favorable conditions for nitrogen removal in the combined SBF – AS system. During normal operation, the influent NH_4^+ – N concentrations were higher than those in design sometimes. However, in comparison with the trial running period, the removal efficiency was improved significantly, which indicated that the nitrobacteria and denitrobacteria were growing up to maturation continuously in the combined SBF – AS system, in the biofilm in particular.

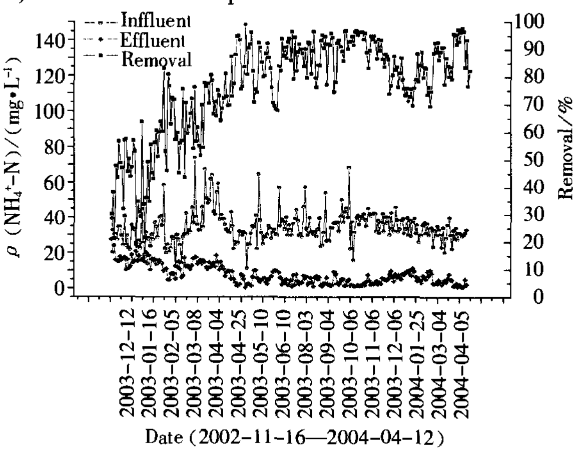


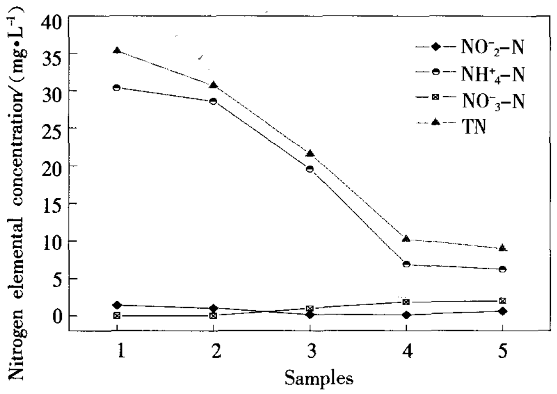
Fig. 5 Variation of NH_4^+ – N concentrations in influent and effluent

2.3.2 Simultaneous nitrification and denitrification (SND) in combined SBF – AS bioreactor

There existed a large quantity of biofilm which attached and grew on the carriers' surface in the combined SBF – AS bioreactor basins. The maturated biofilm in the aerobic corridors had a certain thickness, where existed DO gradient from surface to inside, namely, from aerobic via anoxic to anaerobic zones. Wastewater in the combined SBF – AS bioreactor basins was purified by aerobic, anoxic and anaerobic microbes in biofilm, thus nitrification/denitrification and the degradation of carbonaceous substances taking place simultaneously. The specific structure of biofilm made the DO gradient exist, which developed a favorable micro-environment in biofilm for SND, which makes the combined SBF-AS system superior to conventional activated sludge process and its modified processes[4] in this respect.

Fig. 6 shows the variation of NH_4^+ – N, NO_2^- – N, NO_3^- – N and TN in different zones of the combined

SBF - AS system. In operation periods, the nitrification and denitrification took place in a different part of the combined SBF - AS reactor basins. Oxygen was needed in the process when NH_4^+ - N was biologically oxidized to NO_2^- - N and further to NO_3^- - N, and nitrification process took place in the aerobic corridors as well, where the NH_4^+ - N and TN concentrations decreased simultaneously with the increase of NO_x^- - N concentration. As shown in Fig. 6, the decrease of NH_4^+ - N concentration is much higher than the increase of NO_x^- - N, which means that a major part of ammonia nitrogen was removed via nitrification and denitrification with the production of N_2 within biofilm due to DO gradient which resulted in anoxic/anaerobic conditions, and hence low NO_x - N concentration. In addition, a part of NH_4^+ - N also participated in the synthesis of new microbial cells. It can be concluded that, in the combined SBF - AS bioreactor basins, the nitrification and denitrification took place simultaneously and NH_4^+ - N and TN were removed efficiently.



1. Inf.; 2. Effl. of anaerobic corridor; 3. Effl. of aerobic corridor 2; 4. Effl. of aerobic corridor 4; 5. Effl. of aerobic corridor 5

Fig. 6 Variation of nitrogen concentration in different units

2.4 Phosphorus Removal

In Dong'e WWTP, the biological phosphorus removal process was achieved in the combined SBF - AS reactor basins based on the activity of phosphorus-accumulating organisms (PAOs) by returning sludge from final clarifiers to pre-anoxic and anaerobic zones. In the anaerobic zone, PAOs took up readily biodegradable organic carbon substrates and stored them as polyhydroxyalkanoates (PHAs). The energy to this anaerobic process were derived from the hydrolysis of intracellular polyphosphate and the glycolysis of glycogen followed by the release of orthophosphate to the bulk liquid [5-6]. In the subsequent anoxic and aerobic zone, PAOs used the PHAs for generating energy for growth and phosphate uptake, where the PAOs took up phosphate more than the released one in the anaerobic phase (luxury uptake). Finally, the phosphorus is removed through discharge of excess sludge from this system.

The variation of the TP concentration is shown in Fig. 7. The influent TP varied between 1.1 - 14.4 mg/L (mean 3.7 mg/L) and mean of effluent from clarifiers is 0.8 mg/L. The mean removal efficiency of total phosphorus is 75%.

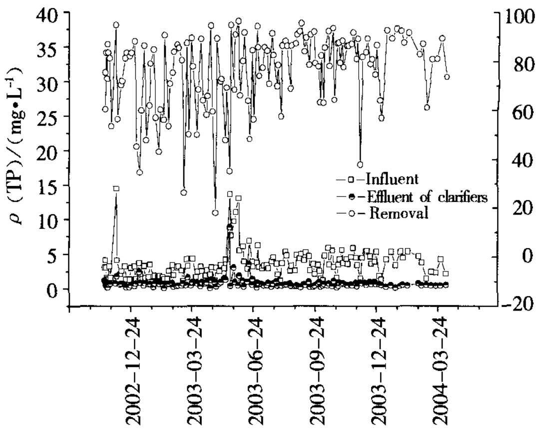


Fig. 7 Variation of TP concentration in influent and effluent

In the operational periods, the influent TP concentration was not very high, the mean values of BOD_5, NH_4^+ - N and TP are 160.6 mg/L, 34.3 mg/L and 3.7 mg/L respectively with the ratio of m (C) : m (N) : m (P) = 100 : 21.3 : 2.3. In the whole system, the phosphorus was mainly removed by microbial metabolism and the PAOs in suspension acted as activated sludge in the combined SBF - AS basins, which released phosphorus in the anaerobic zone and took up excess phosphorus in the aerobic and anoxic zones.

Some studies indicated that the ratio of biodegradable organic substrate to total phosphorus (BOD_5/TP) in the anaerobic zone was the most important factor that affects PAOs uptake efficiency. In the anaerobic zone, PAOs firstly took up the substance as volatile fatty acid with small molecular weight. To obtain the high quality of effluent with TP concentration below 1 mg/L, the influent BOD_5/TP ratio of 20 - 30 was sufficient for PAOs uptake of TP. In Dong'e WWTP, the influent BOD_5/TP ratio was about 44, which means that there was high organic substrate in the anaerobic zone and in the whole operation period, which made the TP concentration in effluent almost below 1 mg/L without additional chemical phosphorus removal process.

2.5 SS Removal

As shown in Fig. 8, the influent SS had a sharp variation from 40 to 645.5 mg/L, and the effluent SS maintained stable without any significant variation with the mean removal efficiency of 92%. The design of 16 perforated stainless outlet pipelines with respective water – level adjustable overflow weirs was employed in the final clarifiers, which performed very well with very clear effluent, and low SS concentration in effluent.

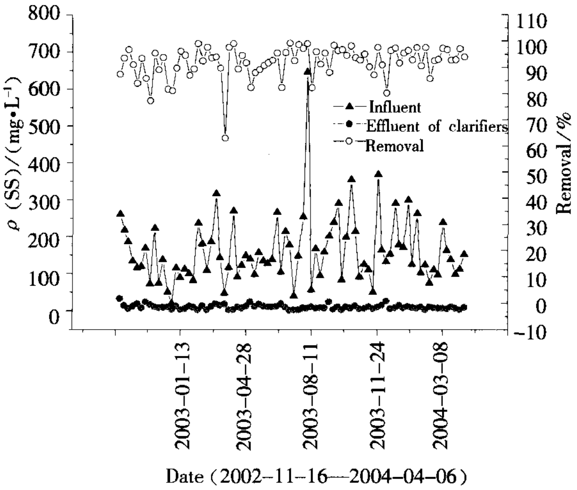


Fig. 8 Variation of SS concentration in SBF – AS system

2.6 Operation Cost

From one year's operation in Dong'e WWTP, the combined SBF – AS process not only had the high quality effluent but also low operation and maintenance costs. In Dong'e WWTP, the mean value of energy consumption was 0.18 Yuan (About US \$ 0.02)/m^3. The wastewater treatment cost was 0.28 Yuan (about US \$ 0.034)/m^3 without calculating depreciation charge, and 0.45 Yuan (about US \$ 0.055)/m^3 including depreciation charge.

3 Conclusion

It is indicated from more than one year's operation in Dong'e WWTP that the combined SBF – AS process has the advantages of simple flow chart and system, easy operation and maintenance, stable and high quality of effluent, high resistance to sharp load shock, low capital and operational costs, and is a highly effective and efficient treatment process that is preferably employed in small towns and cities.

It is also well proved by more than one year's operational results in Dong'e WWTP that the combined SBF – AS system exhibited stable operation efficiency and was very effective and efficient in organic, nitrogen and phosphorus removal by means of both the attached growth biofilm and suspended biomass (activated sludge) in which the biological phosphorus removal and simultaneous nitrification/denitrification took place in the combined SBF – AS bioreactor system.

References:

[1] MORPER M R. Full scale application of specialized biological processes for advanced wastewater treatment[J]. Proceedings of International Conference on Water and Wastewater, 1994,2:661 – 669.

[2] ODENNGAAD H. Advanced compact watewater treatment based on coagulation and moving bed biofilm processes [J]. Wat Sc Tech, 2000, 42(12):33 – 48.

[3] ODENGAAD H, RUSTEN B, WESTRUM T. A new moving bed biofilm reactor—Application and result[J]. Wat Sci Tec, 1994, 29(10 – 11): 157 – 165.

[4] WANG B Z, LI J, WANG L. Mechanism of phosphorus removal by SBR submerged biofilm system[J]. Water Research, 1998, 32(9): 2633 – 2638.

[5] WANG B Z, YANG Q D, LIU F R, *et al.* A study on simultaneous organic and nitrogen removal by extended aerated submerged biofilm process[J]. Wat Sci Tech, 1998, 24 (5):197 – 213.

[6] HARREMOES P. Advanced water treatment as a tool in water scarcity management[J]. Wat Sci Tech, 2000, 42 (12):73 – 92.

[7] LEE D S, JEON C O, PARK J M. Biological nitrogen removal with enhanced phosphate uptake in a sequencing bacch reactor using single sludge system[J]. Wat Res, 2001, 35(16):3968 – 3976.

[8] MINO T, ARUN V, TSUZUKI Y, *et al.* Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal process[A]. Proceedings of the IAWPRC International Conference on Biological Phosphate Removal from Wastewater [C]. Rome: Adv Water Pollut Cont, 1987.