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Enhanced Nutrient Removal with Upflow Biological Aerated Filter for Reclaimed Water

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Abstract: A two-stage upflow biological aerated filter was designed as an advanced treatment process to optimize the operating parameters and study the correlative factors influencing the efficiency of nitrification, denitrification and phosphorus removal. The experimental results showed that the final effluent of the two-stage upflow biofilter process operated in series could meet the stringent limits of the reclaimed water for the total nitrogen of 2 mg/L, and total phosphorus of 0.3 mg/L. The high treatment efficiency allowed the reactor operating at very high hydraulic loadings and reaching nearly complete nitrification and denitrification.

Key words: biological aerated filter; nitrification; denitrification; nitrogen and phosphorus removal; reclaimed water

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Many cities located in coastal or inland areas are facing with the thorny problems on the shortage of water resources. And they have to experience the severe lack of water for recreational and environmental uses, such as the development of recreational lakes, marsh enhancement, and stream-flow augmentation. For the prior supply of drinking water, water for scenic environment use in these areas has to be replenished with reclaimed water. For example, reclaimed wastewater from the Tillman Water Reclamation Plant has been used to maintain the park pond at the Japanese Garden in Los Angeles[1], incorporated into urban landscape developments. In a semi-arid country such as Israel, reclaimed wastewater is the most feasible water source for river recovery. The Administration for the Recovery of Israeli Rivers already initiated some projects where reclaimed wastewater serves as the main water source for the recovery of rivers and streams[2-3].

The adverse influence of nitrogen and phosphorus on the water quality can not be neglected. It is generally accepted that eutrophication is the result of excessive nutrient loadings of nitrogen and phosphorus[4-5]. Eutrophication can result in the undesirable presence of algal blooms. These nuisance growths of algae adversely affect water quality, impair downstream water treatment processes and restrict recreational activities in the vicinity[6-8].

Consequently, the requirements of reclaimed water for nitrogen and phosphorus will be more stringent in view of eutrophication in many areas. For example, the Olympic Lake of Beijing is planned to be supplied by reclaimed water which must meet the stringent standards for the total nitrogen of 2 mg/L, and total phosphorus of 0.3 mg/L.

To meet the requirements, a two-stage sub-

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merged upflow biofilter was designed in this study, as an advanced treatment process, for the further removal of suspended solids, organic matters, ammonia, nitrate and phosphorus from the effluent of a wastewater treatment plant.

Biological aerated filter is an alternative to the traditional activated sludge process commonly used in biological wastewater treatment, and is well suited for expanding or upgrading plants[9-10]. Smaller reactor volumes and the absence of secondary clarifiers results in a system that uses about one third the footprint surface of an activated sludge system[11]. This fixed film process develops a much higher concentration of active biomass than the suspended growth activated sludge system, and is particularly adapted for further treating effluent of secondary treatment with low organic substrate concentration[12-13]. Nitrification and denitrification can be carried out efficiently in biological aerated filter[14-16], and phosphorus removal by metal salt addition has been proved feasible.

The experiment employed an aerated filter to remove the residual organic carbon and to oxidize ammonia, and an anoxic filter for denitrification with the external carbon source of methanol. Besides, phosphorus was removed by micro-flocculation filtration with $FeCl_3$ addition to the filters. The main goals of this study were to investigate whether the water quality of the tertiary effluent treated by the two-stage upflow biofilter can meet the requirements for the reclaimed water supplied to Beijing Olympic Lake, optimize the operating diameters of bioreactors, and study the correlative factors affecting the efficiency of nitrification, denitrification and phosphorus removal by chemical method.

1 Materials and Methods

1.1 Experimental Apparatus and Operation

A schematic of the reactors used in this study is shown in Fig. 1. The two columns, operated in series, were both 3 m in height and 100 mm in diameter. The expanded clay granular media, approximately 2 to 4 mm in diameter with an average specific surface area of 9 000 to 10 000 cm^2/g and voidage of 0.4, was packed in both of the columns with a bed height of 1.8 m. Each column was provided with 12 sampling ports which were set one every 15 cm from the bottom of the media, allowing for both liquid and media and for measuring the head losses during filter operation. The feed entered from the columns bottom with the flow rate ranged from 5 to 130 L/h (delivered via a peristaltic pump, model ZT60-600 Lange, Baoding, China). One of the columns was aerated through a submerged diffuser at the bottom for the further removal of organic material and complete nitrification. Another column used as an anoxic filter was fed with effluent from the aerated filter, for denitrification with methanol as carbon source. Metal salt was added respectively into the two filters to study the efficiency of phosphorus removal. The relation between treating efficiency and hydraulic loadings was investigated by adjusting flow rates. Sometimes effluent of several aerated columns was used as influent of the anoxic filter owing to its higher treatment capacity.

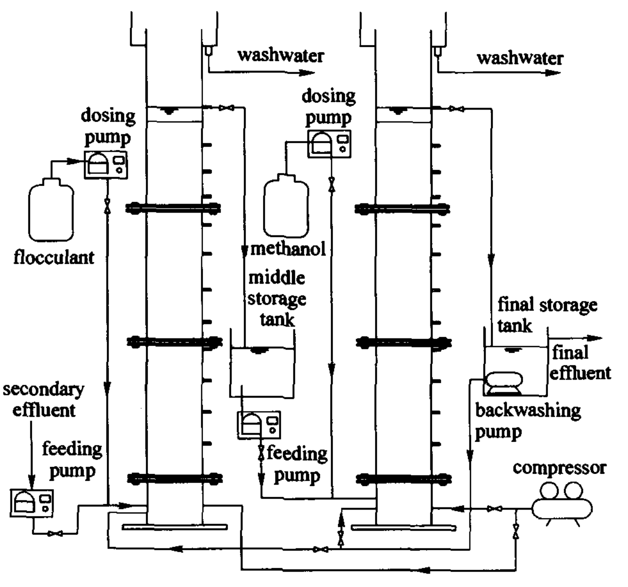

Fig. 1 Schematic of the two-stage up-flow biological aerated filter

Filter backwashing was established according to the increase of the head losses within the filter, and a set value of 100 cm of water column as maximal assumable head loss. Backwashing conditions were the following: 2 min air scour at 50 m/h followed by 5 min air scour at the same flow rate combined with backwash at 40 m/h. Finally, air flow was stopped and the column was washed with final effluent pumped from a storage tank at 40 m/h for 3 min. Then the column was drained down before the flows recommenced.

1.2 Influent Characteristics

The influent of the aerated filter was supplied with the effluent from a pilot-scale A/O activated sludge reactor. Tab. 1 presents the characteristics of the influent. As shown in Tab. 1, the effluent from the pilot-scale A/O reactor was similar to the secondary effluent from the actual wastewater treatment plant.

Tab. 1 Characteristics of the aerated filter influent

value	COD/ $(mg \cdot L^{-1})$	BOD_5/ $(mg \cdot L^{-1})$	SS/ $(mg \cdot L^{-1})$	NH_4^+ - N/ $(mg \cdot L^{-1})$	NO_2^- - N/ $(mg \cdot L^{-1})$	NO_3^- - N/ $(mg \cdot L^{-1})$	TP/ $(mg \cdot L^{-1})$	pH	temperature/ ℃
range	45 - 85	19 - 37	8 - 38	8 - 45	2 - 3	15 - 46	6.0 - 8.5	6.9 - 7.4	15 - 27

1.3 Sampling and Analysis

For all liquid samples COD, BOD_5, SS, NH_4^+ - N, NO_2^- - N, NO_3^- - N, TP were measured according to standard methods. Temperature, pH and dissolved oxygen were measured using WTW inoLab level 2 hand-held instruments. The biomass attached to granular media was determined by direct gravimetry, and expressed as volatile attached solids (VAS) in mg/g (miligram VAS per gram substratum)[17]. The specific activity of microorganism expressed as specific oxygen uptake rate (SOUR) was measured by closed respirometry. SOUR of heterotrophs, autotrophic ammonia and nitrite oxidizers was determined through adding the selective biological inhibitors $NaClO_3$ and allylthiourea (ATU) at different time for ammonia and nitrite oxidizers respectively during testing process[18], and expressed as mg/(g·h)(miligram O_2 per gram VAS per hour).

2 Results and Discussion

2.1 Ammonia Removal

The influent and effluent ammonia concentrations and removal rates are shown in Fig. 2. The nitrification efficiency was tested in the range of influent flow rate from 8 to 40 L/h. In order to study the performance of nitrification with high influent ammonia concentration, ammonium was added into the secondary effluent to increase the ammonia concentration in the late process, the corresponding flow rates were 16 and 32 L/h. Given that the standard of complete nitrification is that the outlet ammonia concentrations are not higher than 1 mg/L, to meet the requirement, the ammonia applied loading rates of the reactors are lower than 0.6 kg/(m^3·d), and the hydraulic loadings range from 1 to 5 m/h. Fig. 3 shows that the relationship between the applied and removed loading rate is linear, and the ammonia eliminated loading rates increase with the applied loading rates. Nevertheless, the ammonia removal rates is lower than 90% when the eliminated loading rates exceed 0.6 kg/(m^3·d). Thus it is not suited for the aim of controlling the total nitrogen concentration below 2 mg/L. By investigating the variation of ammonia eliminated loading rates under two different water velocities, it can be seen that the ammonia removal efficiency is higher at influent flow rate of 32 L/h than

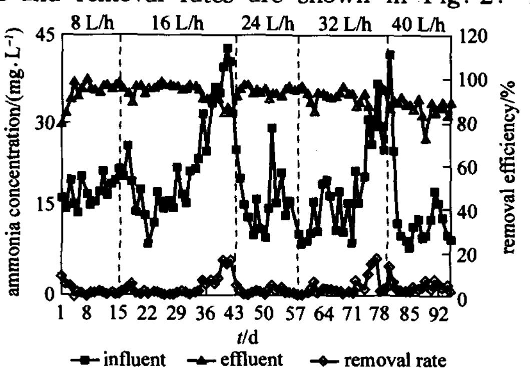

Fig. 2 Profiles of nitrogen concentrations and removal rates

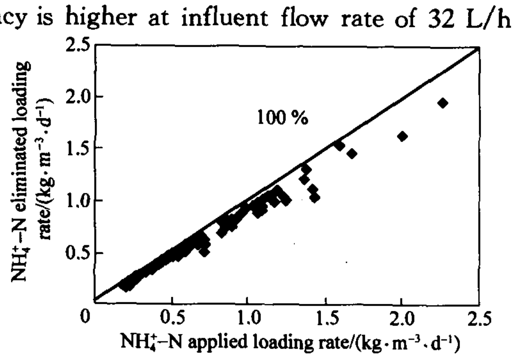

Fig. 3 Relationship between ammonia applied loading rate and removed loading rate, and the ammonia removal efficiency

that at flow rate of 16 L/h. For example, at the ammonia applied loading rate of 1.06 $kg/m^3 \cdot d$, the removal efficiencies at flow rate of 16 L/h and 32 L/h are 90% and 98% respectively. It indicates that higher water velocity result in higher removal rate within a certain range of ammonia applied loading rates (Fig.4).

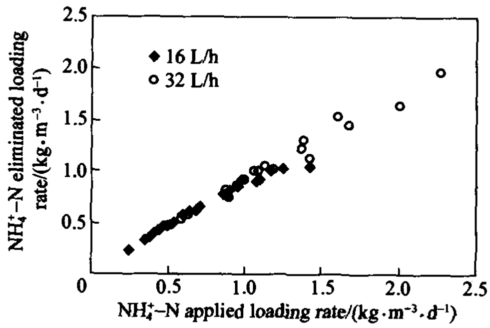

Fig.4 Influence of the different water velocities on ammonia removal efficiency

It is found that the influent COD concentration influences the nitrification capacity. As shown in Fig.5, ammonia loading rates are divided into two parts according to the influent COD concentration, and the COD concentration of 50 mg/L is the division. It can be observed that the ammonia eliminated loading rates decrease when the inlet COD exceed 50 mg/L. And with the increase of ammonia applied loading rates, ammonia eliminated loading rates decrease more. The competition between heterotrophs and nitrifiers for space and oxygen is the cause of the above phenomenon. The increased COD load applied to the aerated filter pushes the region of the filter where maximum nitrification activity occurs further up the column, that results in the decrease of the nitrification efficiency. The experiment increases the

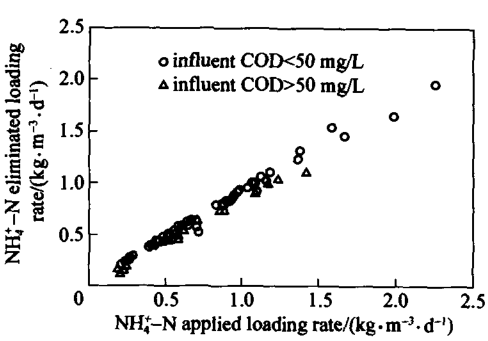

Fig.5 Influence of the influent COD concentration on nitrification

ammonia applied loading rates through increasing hydraulic loadings, companied with the increase of the COD applied loading rates, therefore the nitrification of system is affected. Fig.6 shows the biomass concentration and the activities at the distance of 0.3, 0.6, 0.9, 1.2, 1.5 m through filter when the ammonia applied loading rates is 0.6 $kg/(m^3 \cdot d)$. It can be seen that the activities of heterotrophs are lower than nitrifiers activities through the whole column, and the highest heterotrophic activity occus at the bottom of the filter, therefore organic matters are degraded near the inlet of the reactor easily. This characteristics of the biomass growth are different from the reactor treating sewage. The biomass concentrations are basically constant at the bottom and the middle of the column, only decrease near the outlet. The feature indicates that the lower organic substrate concentrations limit the growth of heterotrophs.

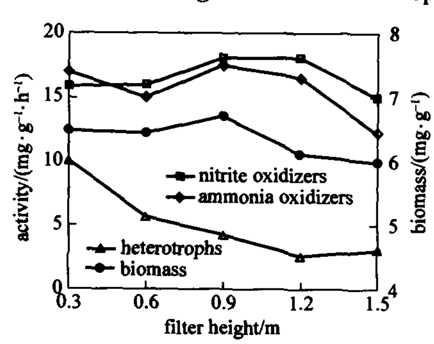

Fig.6 Profiles of the biomass concentration and the activities of ammonia oxidizers, nitrite oxidizers and heterotrophs

2.2 Denitrification Rate

The denitrification rates are very high with methanol as the external carbon source in the anoxic filter. The denitrification efficiency is equal to or close to 100% with the applied loading rates up to 6 $kg/(m^3 \cdot d)$ (Fig.7). As shown in Fig.7, the relationship between the NO_3^- - N applied and eliminated loading rates is linear, too. Even if the water velocity reaches 16 m/h, when the theoretic hydraulic retention time is only 6.52 min, and the actual hydraulic retention time is 2.8 min (consider that parts of the volume of the filter is occupied with media and biofilm), it also achieves the steady nitrate removal efficiency up to 90%. Such a short retention time does not affect the denitrification rates. Measuring the nitrate concentrations along the flow path of the anoxic filter at different water velocities, Fig. 8 shows that the denitrification efficiency is increased with the higher hydraulic loading (the water velocity of 9 m/h and the applied $NO_3^- - N$ loading rate of 2.73 kg/($m^3 \cdot d$)).

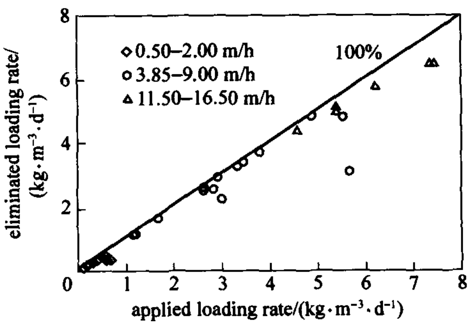

Fig. 7 Influence of the water velocity on denitrification in the anoxic filter

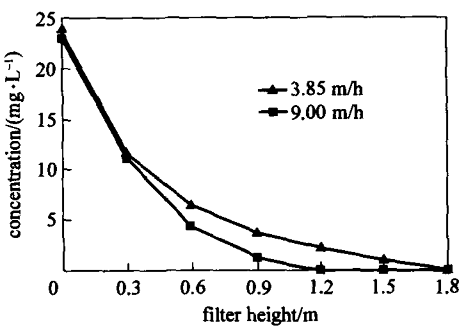

Fig. 8 $NO_3^- - N$ concentration along the filter height at different water velocities

The characteristics of nitrification in the aerated filter and denitrification in the anoxic filter show that higher water velocity can result in higher treatment efficiency within the maximum treatment capacity of the biofilters. The reason of the above phenomena may be that the increase of the hydraulic loadings improves the mass transfer efficiency and the distribution of water.

2.3 Phosphorus Removal by Micro-Flocculation Filtration

In this experiment, empirical testing was used to define the kind and the best dosage of metal salt. $FeCl_3$ was added to the filter with the dose of 30 – 36 mg/L(Fe). $FeCl_3$ needed a rapid mixing with wastewater for a detention time about 1 min using a paddle mixer, then it was pumped to the biofilter to carry out micro-flocculation filtration in the biofilter. Fig. 9 shows the phosphorus removal effects at different filtration velocities when adding $FeCl_3$ to the aerated filter and anoxic filter, respectively. The batch assays showed that the process required enough reaction time after the metal salt mixed with influent and entered the filter, thus the phosphorus removal in the aerated filter at the filtration velocity of 5 m/h performed better than that in the anoxic filter at the filtration velocity of 10 m/h. Outlet total phosphorus concentration was lower than 0.2 mg/L.

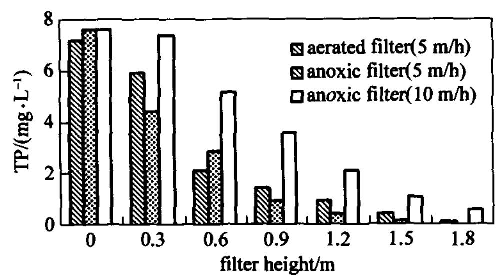

Fig. 9 Phosphorus removal effects at different filtration velocities

3 Conclusions

A two-stage upflow biological aerated filter was designed in this study, as an advanced treatment process, for the further removal of suspended solids, organic matters, ammonia, nitrate and phosphorus from the effluent of a wastewater treatment plant.

The experimental results showed that, when the hydraulic loadings of the aerated filter ranged from 1 to 5 m/h, and the ammonia eliminated loading rates were below 0.6 kg/($m^3 \cdot d$), nitrification could be complete with the outlet ammonia concentrations not higher than 1 mg/L. The highest heterotrophic activity occurred at the bottom of the filter resulted in the degradation of most organic matters near the inlet of the reactor. The increased COD load applied to the aerated filter pushed the region of the filter where maximum nitrification activity occurred further up the column to result in the decrease of the nitrification efficiency. The denitrification efficiency of the anoxic filter was equal to or close to 100% at the applied loading rates up to 6 kg/($m^3 \cdot d$). Adding $FeCl_3$ to the biofilter where micro-flocculation filtration was carried out could obtain the satisfying outlet total phosphorus concentration of lower than 0.2 mg/L.

Even if the water velocity reached 16 m/h in the anoxic filter, when the actual hydraulic retention time was 2.8 min, the steady nitrate removal efficiency up to 90% were still achieved, this indicates the advantage for biofilm process to resist the fluctuation of hydraulic loadings.

The final effluent of the two-stage upflow biofilter process operated in series could meet the stringent limits of the reclaimed water supplied for Beijing Olympic Lake for the total nitrogen of 2 mg/L, and total phosphorus of 0.3 mg/L.

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