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Experimental study on sequencing batch biofilm reactor with biological filtration (SBBR-BF) for wastewater treatment

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Abstract A novel wastewater treatment technology combining a sequencing batch biofilm reactor and biological filtration in an SBBR-BF system was presented. Elastic plastic filaments were fixed as biofilms carrying media. Particle materials (sand or anthracite) and the settled sludge constituted the filtration layer. In the laboratory studies, operating results of SBR, SBBR and SBBR-BF were compared. Better quality and stable water quality of effluent could be achieved in SBBR-BF because the fixed film and filtration layer were added in the reactor. Other laboratory experiment results indicated that slow filtration, cycle water stirring and backwashing making use of the settled supernatant are successful methods for preventing clogging and saving energy. The velocity and headloss of filtration were significantly impacted by different MLSS concentration. The MLSS concentration in the reactor must be less than 1,400 mg/L for optimal results. The average velocity of filtration ranging from 0.6 to 1.0 m/h, the backwash velocity of 10–15 m/h and the backwash time of 20 seconds are recommended according to the laboratory experiment. On-site experiment and study showed that SBBR-BF is a stable and efficient system for domestic wastewater treatment, and is particularly suited for small wastewater treatment plants, because of the simple operation and compact installation.

Keywords Backwashing; biological filtration; SBBR-BF; sequencing batch biofilm reactor; small wastewater treatment system

Introduction

A great deal of small community and industrial wastewater cannot be collected for treatment in centralized wastewater treatment plants. Especially in rural areas, on-site small wastewater treatment plants are of key importance for improving water quality and tackling the problem of this diffuse pollution (Geenens and Thoeye, 2000). Small wastewater treatment systems for decentralized application must provide advanced wastewater treatment; they must be highly effective, robust, easy to operate and low in costs (Wilderer and Schreff, 2000). The sequencing batch reactor (SBR) is one of the most promising technologies for such applications.

Similar to activated sludge SBR systems, the sequencing batch biofilm reactor (SBBR) technology, which uses a packed support medium of biofilms, provides periodic changes in conditions to achieve various wastewater treatments (Wilderer *et al*., 2001). Recently, the SBBR system has been studied and applied extensively since it has many advantages over the conventional activated sludge processes and biofilm processes. The advantages of

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SBBR packed biofilm in comparison with activated sludge systems include: higher biomass concentration in the reactors, larger surface area for fixed bacterial growth, higher volumetric load, better treatment stability, higher specific removal rates, less influence by toxic substances and a compactness in reactors. Furthermore, slow growing organisms can be accumulated easily in a biofilm reactor because sludge age is independent of the mean residence time of the fluid and a smaller quantity of excess sludge is produced (Jaar and Wilderer, 1992; Kaballo, 1997). The advantages of operation of biofilm reactors in a fill and draw mode include: the controlled unsteady-state condition to meet the discharge limits (Wilderer *et al.*, 2001), less mass limitations for oxygen and substrates, relatively decreased clogging of the packing caused by growth of biomass in the inflow section of the reactor and more even biomass distribution throughout the reactor (Kaballo *et al.*, 1995).

As with any wastewater treatment system, the SBBR technology also has certain disadvantages. Under higher influent loads, the suspended solids commonly accumulate in the reactor and the significantly increased biomass can often cause clogging of the packing. In response to high influent loads backwash frequency can be increased, however, excessive backwashing substantially reduces treatment capacity. Furthermore, to prevent plugging of the nozzles and packed carrying medium, it is recommended that suspended solids be eliminated as far as possible before the wastewater is fed into the reactor. Washing water storage tanks and high backwashing flow will reduce the system's effective capacity. In comparison with the activated sludge system, higher dissolved oxygen concentrations are necessary to avoid oxygen depletion in the deeper zones of the biofilm. During the aeration phase, the recirculation pump should also be in operation because the turbulence caused by the rising air bubbles is not sufficient to fully exploit the system's capacity (Wilderer *et al.*, 2001). More energy is required to increase aeration power due to air scour requirements, high influent pumping head and backwash water pumping operation. Because the biofilm carrier materials occupy a considerable fraction of the reactor, the volumetric exploitation of the tank volume nevertheless remains relatively low (Arnold *et al.*, 2000). In fact, diffusion limitations are common in biofilm systems. As a result, only a fraction of the biofilm can contribute to the overall metabolic processes. Frequent washing decreases the overall sludge age in the SBBR system. As regards process efficiency, further improvements in SBBR systems are being developed (Wilderer *et al.*, 2001).

In order to enhance effluent quality, solve the problem of clogging, save energy and eliminate the specialised washing water storage tank for SBBR, the Sequencing Batch Biofilm Reactor with Biological Filtration (SBBR-BF) is presented. SBBR-BF is a hybrid system characterized by sequencing batch biofilm reactor and using slow filtration through various media containing microorganisms. There are many differences from the traditional SBBR, including hydraulic regimes and type of support medium. The SBBR-BF system has fixed elastic plastic filament medium, which provides a surface on which microorganisms can attach and grow. And in this system the wide space between the media avoids clogging of the packing, enhances penetration of contaminants and oxygen into the fixed film, provides higher volumetric rate and does not require the high power levels used to keep all of the mixed liquid and suspended solids in motion. It appears that fixed bioflim and suspended activated sludge work together for contaminant removal in reactors. Normally, effluent quality from the attached growth process may not be good due to oxygen depletion (Hamoda and Al-sharekh, 2000) and many suspended fragments of biofilm are created. Slow media filtration operation was designed to pass treated water by SBBR through three filtration parts (packing, activated sludge and sand or other materials), thus improving effluent quality and eliminating the specialised decantor in SBBR-BF. The settled supernatant is used as backwash for preventing clogging, eliminating washing water storage tank and saving energy. SBBR and BF are compacted in a reactor. It is necessary to

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establish an efficient system for SBBR-BF to accomplish reaction, filtration and preventing of clogging.

Materials and methods

Laboratory experimental system

One of the experiments was carried out in the laboratory and compared effluent quality from SBBR with SBBR-BF for wastewater treatment. Figure 1 shows the schematic diagram. The system characteristics are described in Table 1. The biofilm support medium was made of synthetic plastic filaments strung by cords. Elastic plastic filaments have a coarse surface and radial structure that offers a 120–180 square metre surface per cubic metre volume. The material does not deteriorate in wastewater, retains its strength and elastic properties and holds its dimensional stability. Raw wastewater was taken from fresh domestic sewage that had a variety of parameters. The main characteristics of raw wastewater are listed in Table 2. The operating stages are listed in Table 3. Effluent samples of SBBR were drawn from supernatant after the settling phase, whereas those of SBBR-BF were taken from the filtration water. Another SBR system was also operated under the same conditions but without medium packing. Operation with high loads and low temperature were also studied.

Experimental runs and tests were started after stable operation. The total biomass concentration was about 4,000 mg/L and the sludge age was more than 10 days. Dissolved

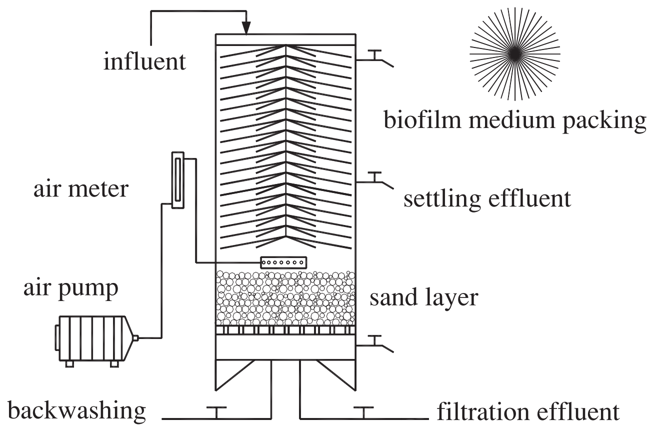

Figure 1 Schematic diagram of comparison of SBBR and SBBR-BF

Table 1 Technical data of the experimental system

No.	Parameter	Unit	Value
1	Total working volume	L	2.8
2	Inner diameter	cm	10.0
3	Total height	cm	36.0
4	Medium packing height	cm	22.0
5	Packing material	Elastic plastic filament	
6	Filtration material diameter	mm	0.625–1.5
7	Filtration material		Sand
8	Depth of filtration layer	cm	6.0
9	Volumetric exchange ratio		70%
10	Air volume stream	L/h	50
11	Filtration velocity	m/h	<0.7
12	Total biomass concentration	mg/L	About 4,000

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Table 2 Characteristics of influent wastewater

Term	COD	Turbidity	NH_4-N	SS	pH	Temperature
Unit	mg/L	NTU	mg/L	mg/L		°C
Average	350	300	35	210	7.3	18.8
Maximum	1400	520	108	410	7.6	20.0

Table 3 The operating stages in the laboratory experimental system

Stage	Feed	Aerobic	Settle	Filtration	Draw
Unit	min.	min.	min.	min.	
SBBR	10	150, 240, 360, 600	90		Settled supernatant
SBBR-BF	10	150, 240, 360, 600	5	<40	Filtration water

oxygen levels were above 2.5 mg/L in the reactor. All samples analysed for COD, NH_4-N and turbidity were tested according to standard methods in China.

The other experiments for filtration and back washing were carried out in the laboratory. Figure 2 shows the schematic diagram of filtration and backwashing in the experimental apparatus. The aims of the experiment were to select a suitable diameter of sand, velocity of filtration, suspended sludge concentration in the reactor and methods to prevent clogging. An experimental column was made of polymethyl methacrylate with a maximum working volume of 10 L and an inner diameter of 10 cm. The thickness of the sand filtration layer was 6 cm and the diameter of the sand was 0.625–1.5 mm. The filtration performance was tested and compared at various velocities of filtration and sludge concentrations in the column. After each period of filtration, a portion of the cycle water was pumped to the top of the sand layer for mixing and stirring the sludge layer and keeping the necessary concentration of mixed liquid suspended solid. The aims of mixing and stirring were to reduce clogging of the sand layer and enhance denitrification. The main testing parameters included variations of filtration velocities and water headloss with filtration times. The conditions of sludge leak and clogging were checked.

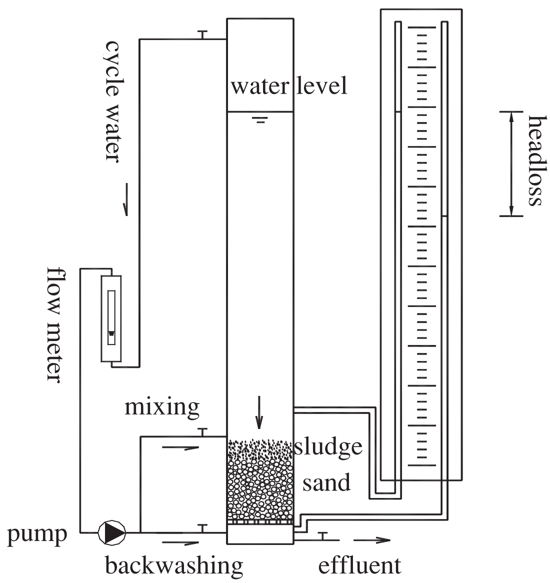

Figure 2 Schematic of filtration and backwashing in experimental apparatus

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A novel method of backwashing was studied in the experiment. The settled supernatant as backwash water was pumped to the bottom of the sand layer for cleaning the filter. At the minimum, the required backwash velocity had to meet the initial fluidisation of the sand. Backwash velocity was further increased to bring about increased sand expansion and cleaning efficiency, but washed sludge was not permitted to upflow into backwash water.

On-site experimental system

According to lab-study results, a pilot scale experimental system of SBBR-BF was designed and constructed on-site near a building on campus. The reactor consisted of a plexiglass vessel with an effective liquid volume of approximately 200 L and height of 110 cm. Schematic layout and operation of the system can be seen in Figure 3 and Figure 4 respectively. Elastic plastic filaments were filled in the reactor as biofilm support media with 1/2 filling rate. Fine bubble diffusers were used as aerators. Perforated pipes were

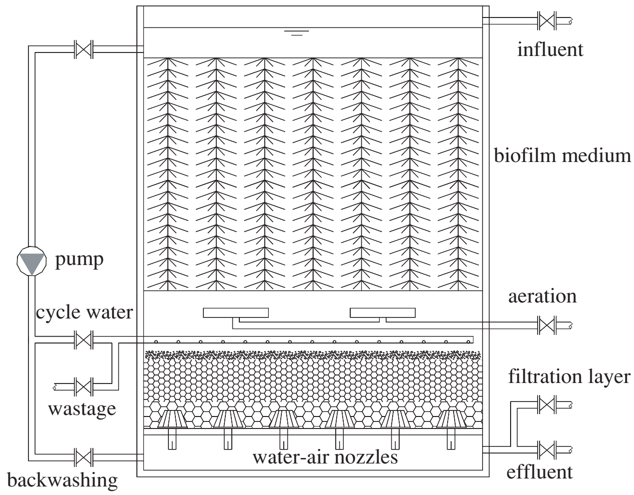

Figure 3 Schematic layout of the on-site SBBR-BF system

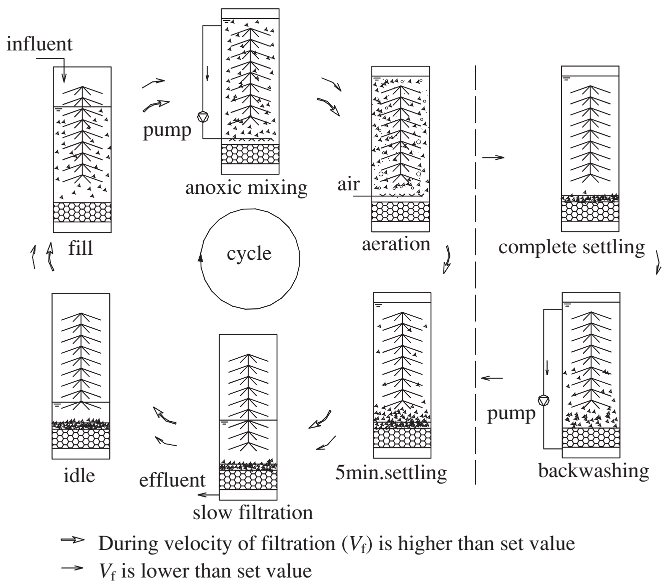

Figure 4 Schematic operating diagram of the on-site SBBR-BF system

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Table 4 The operating stages of the on-site experimental system

Stage	Feed	Anoxic	Aerobic	Settle	Filtration	Idle	Settle	Backwashing
Min.	10	110	300	5	<55	>0	60	<1
	During velocity of filtration (V_f) is higher than set value						V_f is lower than set value	

installed to diffuse the cycled water for mixing and stirring. The filtration layer was filled with anthracite with diameters from 1.0 to 1.6 mm as filtering material and pea gravel with diameters from 2.0 to 3.2 mm as a support matrix under anthracite. Water-air nozzles were constructed at the bottom of filtration layer. The total thickness of the filtration layer was 24 cm.

The operating stages of the on-site experimental system were arranged as in Table 4. The quality of influent is presented in Table 2. The process was operated under the conditions of a total MLSS of about 4,000 mg/L (suspended activated sludge 1,200–1,500 mg/L), SRT >10 d, DO >4 mg/L, average velocity of filtration 0.9 m/h. When average velocity of filtration was lower than the set value of 0.7 m/h, complete settling and backwashing were required. Backwash velocity was about 15 m/h. The C, N, turbidity and velocity of filtration were tested and studied.

Results and discussion

In the laboratory studies, operating conditions of SBR, SBBR and SBBR-BF were compared. Similar to the results of many other studies (Sen *et al.*, 1994), owing to fixed film media in SBBR, nitrification was enhanced and there were better performances under the conditions of high loads and low temperatures. Figure 5 displays a comparison of the mean substrates removal rate in various aeration times. The linear relationship of turbidity and COD of raw wastewater and effluent was found. The results showed the important role of additional filtration for better quality and stability of effluents in SBBR-BF. Interception, diffusion, biological degradation and other physical and biochemical mechanisms occurred through filtration layer processing of activated sludge and sand. Suspended solids and colloidal particles could be reduced from the effluent. This implies that higher efficiency of COD removal in SBBR-BF can be achieved by shortening the reaction time, thus reducing power requirements. Most of the turbidity of effluents was less than 5 NTU. Related to this, soluble ammonia nitrogen easily penetrated through the filtration layer.

In comparison with common SBR, the total time for settling and draw is assumed to be 1.5 hours and water height of drawing is assumed to be 1.0–1.5 metres, thus average velocity of filtration should be 0.6–1.0 m/h in SBBR-BF. The velocity and headloss of filtration

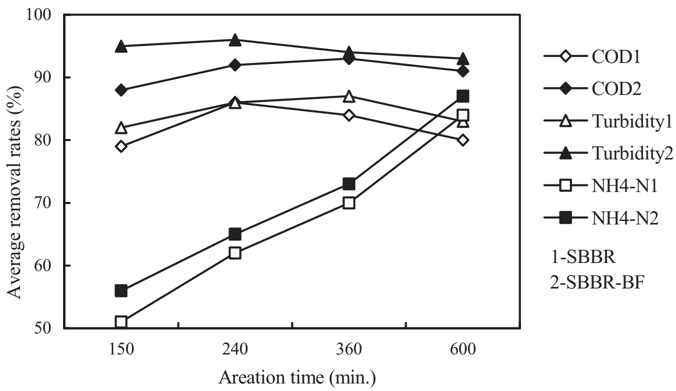

Figure 5 Comparison of removal rates in SBBR and SBBR-BF

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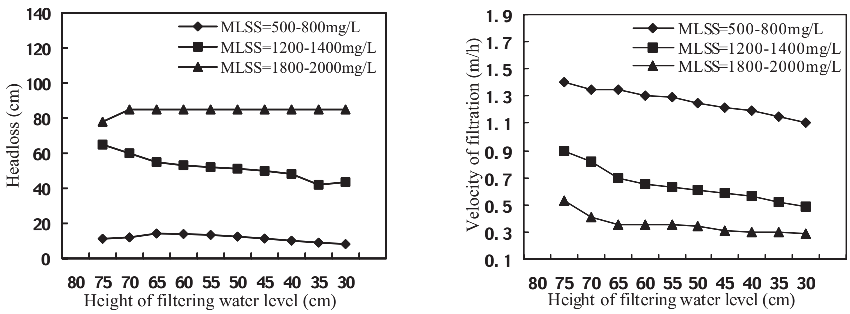
continuously vary with time and position of water level and were significantly impacted by different MLSS concentrations according to the results of filtration. Figure 6 illustrates variations in the velocity and headloss of filtration with water surface level during the first period of filtration in different MLSS concentrations. The filtration was not successfully operated under the condition of MLSS >1,800 mg/L because of high headloss and low velocity of filtration. The experimental results also indicated: the velocity and headloss of filtration had few variations in the following several periods when the condition of the MLSS <800 mg/L, whereas backwashing was necessary after the eighth period when the condition of the MLSS concentration ranged from 1,200 to 1,400 mg/L. As a result, the MLSS concentration in the reactor had to be less than 1,400 mg/L. Reducing MLSS concentration through fixed biofilm in the reactor made a better filtering performance. The experiment also found that a too high velocity of filtration easily caused clogging of the filter and leaking sludge. To meet the operating requirements, slow velocity of filtration ranging from 0.6 to 1.0 m/h in SBBR-BF is recommended. Slow filtration can increase the number of filtration periods and reduce the thickness of the filter because of main clogging in the surface layer.

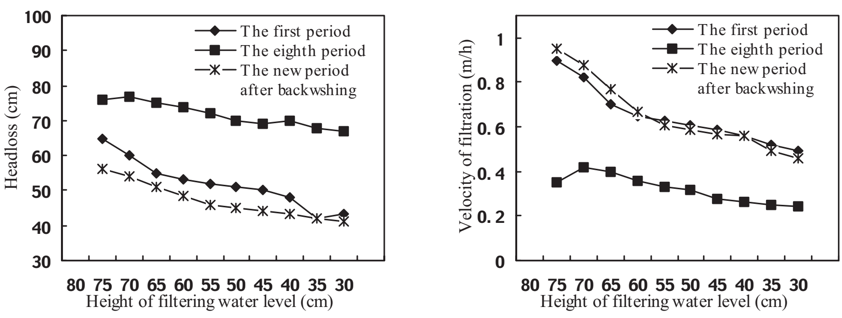
To restore high velocity of filtration, a new method of backwash was used. In the laboratory experiment, backwash velocity was about 10–15 m/h and backwash time was 20 seconds. Backwashing results for MLSS = 1,400 mg/L showed successful operation (Figure 7). With backwash water, the washed sludge upflowed but never reached the top of the reactor during backwashing. The settled supernatant as backwash water eliminated the need for special water storage and made full use of water head of settled supernatant. Energy consumption and construction cost were reduced.

On-site experimental SBBR-BF can be easily started up and be operated stably. Typical results of wastewater treatment are illustrated in Figure 8. Turbidity, COD and TN of



(a) Variations of headloss (b) Variations of velocity

Figure 6 Variations of headloss and velocity of filtration with water level in different sludge concentration



(a) Variations of headloss after backwashing (b) Variations of velocity of filtration after backwashing

Figure 7 Variations of headloss and velocity of filtration after backwashing

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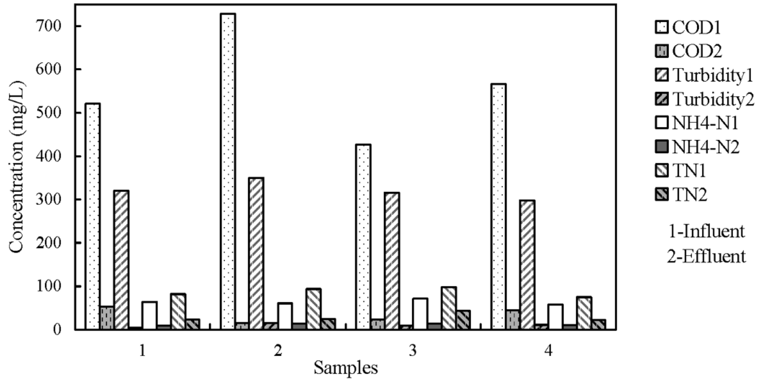

Figure 8 Typical variations of quality of influent and effluent in the on-site SBBR

effluents were very low. The above results imply that the raw wastewater had enough total carbon for denitrification. During three months of operation, backwashing was operated only once since the average velocity of filtration had few variations in about 0.9 m/h. The results also indicate the importance of slow filtration and cycle water stirring for preventing clogging of the filtration layer. According to studies of on-site SBBR, the designed load of 0.3–0.6 kgTN/kgMLSS/d is recommended for domestic wastewater treatment. Without considering the reduction of oxygen transfer efficiency and higher power consumption, aeration through water-air nozzles is also a good method to supply oxygen for full reactor or pre-wash before water backwashing. It is necessary to install a reliable control apparatus for the pump, blower, valves, and instruments for water level, MLSS concentration, DO and pH.

Conclusions

SBBR-BF is a novel wastewater treatment technology that combines SBBR and BF to avoid some disadvantages such as clogging of packing, lower volumetric ratio, requirement of special backwash water storage and higher energy consumption in traditional SBBR. Better quality and stability of effluent could be achieved in SBBR-BF owing to the elastic plastic filaments fixed as biofilm carrying media and the addition of a filtration layer with activated sludge and particle materials. Slow filtration, cycle water stirring and backwashing using settled supernatant are successful methods for preventing clogging and saving energy. The MLSS (excluding fixed biofilm) concentration in the reactor must be less than 1,400 mg/L for optimal results. The average velocity of filtration ranging from 0.6 to 1.0 m/h, the backwash velocity of 10–15 m/h and the backwash time of 20 seconds are recommended according to the laboratory results. The on-site SBBR-BF system was efficient and stable for domestic wastewater treatment, and is particularly suited for small wastewater treatment plants, because of the simple operation and compact installation.

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