Wastewater treatment with submerged fixed bed biofilm reactor systems – design rules, operating experiences and ongoing developments

S. Schlegel and H. Koeser
Martin-Luther-University Halle-Wittenberg, Department of Engineering Science, Institute of Environmental Engineering D-06099 Halle, Germany (E-mail: ust-mail@iw.uni-halle.de)

Abstract Wastewater treatment systems using bio-films that grow attached to a support media are an alternative to the widely used suspended growth activated sludge process. Different fixed growth biofilm reactors are commercially used for the treatment of municipal as well as industrial wastewater.

In this paper a fairly new fixed growth biofilm system, the submerged fixed bed biofilm reactor (SFBBR), is discussed. SFBBRs are based on aerated submerged fixed open structured plastic media for the support of the biofilm. They are generally operated without sludge recirculation in order to avoid clogging of the support media and problems with the control of the biofilm. Reactor and process design considerations for these reactors are reviewed. Measures to ensure the development and maintenance of an active biofilm are examined. SFBBRs have been applied successfully to small wastewater treatment plants where complete nitrification but no high degree of denitrification is necessary. For the pre-treatment of industrial wastewater the use of SFBBRs is advantageous, especially in cases of wastewater with high organic loading or high content of compounds with low biodegradability. Performance data from exemplary commercial plants are given. Ongoing research and development efforts aim at achieving a high simultaneous total nitrogen (TN) removal of aerated SFBBRs and at improving the efficiency of TN removal in anoxic SFBBRs.

Keywords Biofilm; biological wastewater treatment; construction; design; industrial sewage; load based design; municipal wastewater; operational results; submerged fixed bed

Introduction

The fixed biofilm or attached growth technology for wastewater treatment is an alternative to the activated sludge (AS) suspended growth process. These treatment systems, using biomass affixed to the surface of a media, are generally referred to as fixed-growth biofilm reactors (FGBRs) (Albertson, 2000). Different FGBR systems have been applied to the treatment of wastewater.

The commercially most prominent FGBR systems can be classified into three main groups according to the mobility of the growth media, as shown in Figure 1. The combined systems use a combination of AS and fixed biofilm.

Among the different FGBR systems, trickling filters (TF) are especially well known. The rotating biological contactors (RBC) also find wide commercial application. The experience with the other FGBRs is of a more recent nature.

The submerged fixed bed biofilm reactor (SFBBR) is an emerging FGBR that was commercially introduced in Europe in the last two decades. Since then, the use of this process has expanded and its reliability has been established. The operating and design experiences with this technology for the treatment of both municipal and industrial wastewater as well as new developments will be evaluated in the following sections.
Physical design features of SFBBRs

Nowadays, plastic media are almost exclusively used as support or carrier for the biofilm in SFBBRs. They consist of moulded polyethylene (PE), polypropylene (PP) or polyvinyl chloride (PVC), but woven polyester fibres or stripes of PVC films are employed as well. Often the carriers are manufactured in the form of blocks consisting of horizontal perforated cylindrical tubes (PE) or tubes formed by corrugated thin sheets (PP and PVC). Since a considerable exposure to UV radiation may occur during storage and transport carbon and UV stabilisers are often added to the plastic material used for manufacturing the support media.

Media properties that are of primary interest because of their effect on performance are durability, specific surface area density (ratio of geometric surface area to volume) and percent void space. Greater surface density permits a larger biomass per unit volume, while greater void space allows for a higher oxygen and mass transfer to the biofilm and reduces the clogging risks of the channels of the support media by excessive biofilm growth.

Specific surface area densities from 100 to 300 m²/m³ have proven viable. Normally, the support media are manufactured as blocks with a height and side length of approximately 500 mm. The PE blocks have to be factory manufactured. The PVC and PP elements are produced from thin corrugated sheets by gluing or welding either in a factory or at the construction site. Wood or iron support structures have to be provided, especially for woven fibre and plastic stripe materials.

The fixed bed blocks are assembled in the form of easily maintainable modules and aerated from below. Sometimes the necessary air diffusers are integrated into these modules as well. Removable modules allow easy inspection and maintenance preventing the need for plant shutdown during inspection. Besides oxygen supply, the aeration fulfills two additional equally important purposes in the SFBBRs: improving mass transfer and the removal of excess sludge from the fixed carriers by the shearing forces of the turbulent air.

For air supply, coarse or fine bubble aeration systems can be used. A higher utilisation efficiency of air oxygen results from fine bubble aeration. Coarse bubble aeration is more effective in preventing clogging of the bed elements. In addition, coarse air bubbles induce an intensive water movement and act as a mammoth pump thereby improving mass transfer to the biofilm. The higher the fixed bed the better is the efficiency of the aeration system.

If, due to the unsuitability of the used material or its design, the fixed bed reactors clog up, the whole process can collapse. To avoid this, the bed elements as well as the civil works must be designed in such a way that the water flow in the reactor is not obstructed. A well developed circulatory flow ensures a homogeneous mixing of the influent with the reactor content and the transport of the wastewater load to the biomass. Enough free space above and below the fixed bed media supports this type of flow. Figure 2 shows a cross-section of a reactor with the recommended lay-out.

In most cases, submerged fixed bed plants consist of more than one reactor unit arranged in series. The height of the submerged carrier modules can reach 6 m. The total
hydraulic retention time in the fixed bed reactors differs according to the wastewater concentrations and can reach values of more than 1 day. The retention time should not be less than 90 min. Thus, the hydraulic retention in SFBBRs is much longer compared to trickling filters (TF) and biofilters (BF) (Albertson, 2000).

Generally, SFBBR plants are extremely easy to operate, as they are run without sludge recirculation. Only aeration is necessary. The resulting waste sludge is discharged continuously. SFBBRs provide a robust wastewater treatment technology. They are better suited to coping with variations in influent hydraulic flow and loads associated with smaller plants than many other biofilm processes. The simple kind of wastewater treatment makes maintenance requirements minimal, thus saving costs for operating personal and repairs.

To avoid clogging, which is the most critical aspect of this process, an intensive periodic flushing cycle of the fixed bed modules with air is recommendable in order to slough away the excessive biomass. A rate of the flushing air flow of 20 m³/(m².hr) should be applied for approximately 10 min once a day. This flow rate refers to the base area of the carrier modules.

For capacities ranging up to 1,500 people, equivalent factory build turnkey packed treatment plants are available. The reactors for larger flows are designed for side erection and constructed in reinforced concrete.

**Loading based design of SFBBRs**

Aerated submerged fixed bed biofilm reactors are used commercially especially as:
- Pre-treatment stage, mainly for industrial sewage and wastewater from large canteens.
- Biological wastewater treatment stage with or without nitrification.
- Separate nitrification stage within a multi stage treatment process.

According to the DWA (German Association for Water, Wastewater and Waste) SFBBRs will, at operating temperatures of 15 ± 5°C, consistently provide for municipal wastewater removal rates for the BOD (biological oxygen demand) ≥ 95%, COD (chemical oxygen demand) ≥ 80% and TKN (Total Kjeldahl Nitrogen) ≥ 90% if certain load based design rules are followed (ATV, 1997).

For BOD removal without nitrification one should select the total growth surface of the submerged fixed bed sufficiently that the specific BOD surface load is ≤ 12 g/(m².d). The design rules for BOD removal are valid for a wide temperature range from 5 to 35°C, as has been shown recently (Chapanova, 2006).

To achieve a sufficiently high TKN removal, one should design with a TKN surface load of ≤ 2 g/(m².d). This fixed bed surface area has to be added to the necessary area resulting from the BOD calculation since BOD and TKN removal take place successively.
Nitrification is more temperature sensitive and has a longer start up phase than BOD removal. If high BOD concentrations have to be removed it can be advantageous to install an intermediate sedimentation tank between the BOD reducing and the nitrification stage in order to improve the nitrification capacity (Schlegel and Teichgraeber, 2000).

Simultaneous TN (total nitrogen) elimination without a separate denitrification stage is higher in SFBBRs, as in conventional activated sludge plants. Approximately 40–50% of the TKN-load of municipal wastewater can be eliminated simultaneously in aerated SFBBR treatment plants (Schlegel and Teichgraeber, 2000). The reason for this behaviour can be explained with the existence of different autotrophic nitrogen converting bacteria (i.e. Anamox) found in the biofilm (Chapanova, 2006).

Anoxic denitrification can be achieved but is more complicated than denitrification within the AS process. Therefore, only a few anoxic SFBBR plants have been designed so far and no validated data are available for designing anoxic submerged fixed bed pre- or post-denitrification stages. According to some pilot plant results, denitrification in anoxic SFBBRs can be assumed to be sufficient for specific NO3-N-surface-loads \( \leq 2.5 \text{ g/m}^2\text{d.} \) However, as flow resistance is high in submerged fixed bed modules a considerable energy input is necessary for mixing the reactor content in the anoxic operation regime where no mixing is provided by air. As recent plant results show with pre-denitrification SFBBRs consisting of down-flow submerged fixed beds, high stable TN elimination is possible (Kohnert et al., 2006). To prevent clogging problems these beds have to be aerated for some minutes each day.

In the case of municipal wastewater a simultaneous removal of phosphorus of 20–50% is frequently achieved in SFBBRs (Schulz-Menningmann, 1999). For more efficient elimination of phosphorus, chemical precipitation has to be integrated into the SFBBR plant.

Production of surplus sludge in SFBBR plants is often lower compared to the AS sludge process. If no test results are available it can be assumed that not more than 0.5 kg sludge per kg BOD will be produced. Plant experience shows that much lower sludge yields are common. SFBBR plants for municipal wastewater produce usually a compact sludge with good settling-properties.

As SFBBRs are operated without sludge recirculation a sludge clarifier depth of 2.5 m is sufficient. No reports of filamentous bulking of sludge from SFBBRs are available as they are common for AS processes.

As a rule of thumb, the design rules result in a total SFBBR plant volume for the treatment of domestic wastewater of approximately 0.2 m\(^3\) per person equivalent.

**Combined activated sludge and submerged fixed bed biofilm processes**

The conventional submerged fixed bed systems are operated without recirculation of sludge from the final clarifier. In the so-called integrated fixed film activated sludge (IFAS) process sludge is recycled as in the conventional AS process. The biomass attached to the surface of the integrated submerged fixed beds is increasing the biomass density per unit reactor volume over the values provided by the suspended biomass in an AS process. In this way, improved TKN removal rates can be achieved.

Results from commercial plants show that the combination of AS and submerged fixed bed biofilm technology has a tendency for providing a habitat for higher organisms (Schlegel, 1988). These organisms may reduce the fixed biomass on the submerged beds and may influence the sludge settling properties to such an extent that the sludge retention can not be guaranteed any longer and the effluent COD is increasing. Experience has shown that the excessive growth of higher organisms, especially worms in IFAS systems can be controlled by intermittent aeration.
Another problem with IFAS processes is their increased risk of clogging of the channels of the fixed beds. Improving the hydraulic flow through the fixed beds of IFAS by installing efficient mixers, using flexible support material like woven filaments or plastic stripes and efficient aeration will decrease clogging problems and increase mass transfer.

Last but not least, economic consideration has shown that 1 m$^3$ fixed bed substitutes only 1.4 m$^3$ AS tank volume. However, reinforced concrete for an AS tank is much cheaper than the plastic media of the fixed bed modules. The economy of a fixed bed based IFAS process may improve if an already existing plant has to be upgraded for higher TKN removal.

Performance of wastewater treatment plants with SFBBRs – treatment of municipal wastewater

The performance of SFBBRs for the treatment of municipal wastewater was investigated in detail in a small plant for 2,500 people over a time period of 2 years. The plant consisted of four independently operated lines. In this way, at the same time the effect of four different operational parameters could be compared under identical conditions. In front of the four SFBBRs a screen and grit chamber were positioned. Each line was equipped with one primary sedimentation tank, six cascade type submerged fixed bed tanks and one final rectangular clarifier tank.

The following effects of operation parameters have been investigated:

- load on BOD and TKN removal;
- intermittent aeration on energy consumption;
- recirculation and pre-denitrification on TN removal.

COD load varied between 6 and 12 g/(m$^2 \times $ d) with peak loads up to 20 g/(m$^2 \times $ d).

With regard to COD removal it was shown that:

- COD-removal was hardly influenced by the loads investigated;
- intermittent aeration with nonaerated sequences of 30 min/hr had no influence on the COD concentration of the effluent.

With regard to TKN removal the following results were obtained:

- nitrification was depending on the specific load and aeration conditions;
- total surface loads below 8 g COD/(m$^2 \times $ d) guaranteed full nitrification for water temperature between 10 and 20 °C;
- intermittent aeration reduced the nitrification rate though enough oxygen was available in the bulk liquid. Obviously mass transfer of oxygen and substrate to the biofilm was restricted during the non-aerated periods by the lack of sufficient turbulence.

With regard to TN removal it was noted that:

- intermittent aeration reduced the effluent TN concentrations only slightly;
- high recirculation rates from the outlet to the pre-denitrification stage did not result in sufficient TN removal because excessive oxygen was transferred to the anoxic stage.

The average operational results with municipal wastewater are summarised in Table 1.

The investigation showed that SFBBRs are efficient and robust for COD and TKN removal. They can also be used as separate nitrification stage, e.g. in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent</th>
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<tbody>
<tr>
<td>Wastewater flow</td>
<td>m$^3$/d</td>
<td>150–1,300</td>
</tr>
<tr>
<td>COD surface load</td>
<td>g/(m$^2 \times $ d)</td>
<td>6–12</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>100–900</td>
</tr>
<tr>
<td>TKN</td>
<td>mg/L</td>
<td>20–80</td>
</tr>
<tr>
<td>TN</td>
<td>mg/L</td>
<td>20–80</td>
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<tr>
<td>Temperature</td>
<td>°C</td>
<td>10–20</td>
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combination with lagoons. Aerated SFBBRs will remove a considerable amount of the TN simultaneously.

Treatment of industrial wastewater

SFBBRs have been applied successfully for the pre-treatment of industrial wastewater before discharge to a municipal wastewater treatment plant. Pre-treatment is most advantageous in cases of high-strength organic wastewater or wastewater containing hardly degradable components. In the case of highly concentrated influents, recirculation of the effluent to the inlet has proven to be advantageous to prevent toxic concentrations (Schlegel and Teichgräber, 2000).

The results of three commercial SFBBRs for the pre-treatment of wastewater from food and tar processing as well as carpet dying will be discussed below.

**Example 1: Food processing**

The total volume of the SFBBR is 4,000 m$^3$. In the reactor tank, 2,700 m$^3$ fixed bed elements with a specific surface density of 150 m$^2$/m$^3$ are installed. The average treatment results obtained are given in Table 2.

As there is a lack of nutrients in the influent liquor from the sludge, treatment is charged to the reactor as well. It has to be mentioned that this plant is out of operation from end of December till April. In spring when new vegetables are harvested, process operation starts again and reaches full purification capacity within some hours only.

**Example 2: Tar processing**

In this case the total volume of the SFBBR is 5,000 m$^3$ and 4,000 m$^3$ of fixed bed elements with a specific surface density of 150 m$^2$/m$^3$ are installed. Due to the high influent COD concentrations, a supplementary clarifier tank was installed between the COD and the TKN removal tanks to improve nitrification. Treatment results are listed in Table 3.

An additional positive side effect of the treatment was that many toxic and persistent organic components of the tar wastewater were reduced below their detection limits. In the case of the wastewater from tar processing plant, as well as in other commercial and pilot plants, a trend towards gradual adaptation of the attached biomass of the SFBBR to

**Table 2** Average influent and effluent parameters of a SFBBR plant operating on wastewater from food processing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent</th>
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<tbody>
<tr>
<td>Wastewater flow</td>
<td>m$^3$/d</td>
<td>0–9,600</td>
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<tr>
<td>COD surface load</td>
<td>g/(m$^2$.d)</td>
<td>0–45</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>500–4,000</td>
</tr>
<tr>
<td>TKN</td>
<td>mg/L</td>
<td>10–90</td>
</tr>
<tr>
<td>TN</td>
<td>mg/L</td>
<td>5–35</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>10–20</td>
</tr>
</tbody>
</table>

**Table 3** Average influent and effluent parameters of a SFBBR plant operating on wastewater from tar processing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater flow</td>
<td>m$^3$/d</td>
<td>1,000–4,000</td>
</tr>
<tr>
<td>COD surface load</td>
<td>g/(m$^2$.d)</td>
<td>10–45</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>1,000–3,000</td>
</tr>
<tr>
<td>TKN</td>
<td>mg/L</td>
<td>100–500</td>
</tr>
<tr>
<td>TN</td>
<td>mg/L</td>
<td>100–500</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>15–35</td>
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</table>
persistent wastewater components could be observed. As a consequence, the effluent COD is declining over time. The adaptation of the biofilm concerning improved effluent results may take months to years.

Example 3: Carpet dying
The total volume of the SFBBR is 1,400 m$^3$ supplied with 800 m$^3$ fixed bed elements with a specific surface density of 150 m$^2$/m$^3$. The inflow is characterised by a high content of hardly degradable constituents. A marked adaptation was observed over a time of some years. The results are summarised in Table 4.

Conclusions
It has been shown that submerged fixed-bed biofilm reactors (SFBBRs) have been successfully applied especially for:

- small municipal wastewater treatment plants and;
- pre-treatment of industrial sewage.

Wastewater treatment plants with SFBBRs are easy to operate and do not need much supervision. Their space requirement is considerably lower than for an activated sludge treatment plant. Plants reach their full COD removal capacity within hours even after longer stand-still periods.

As pre-treatment plants, SFBBRs can be subjected to high BOD loads without resulting in high sludge indexes and sludge settling difficulties.

As a result of the adaptation of the biofilm attached to the submersed fixed bed elements in the course of time, the treatment of hardly degradable industrial effluents may also be possible.

Ongoing development on SFBBR aims at improving the simultaneous and anoxic TN elimination and on realising more reliable techniques of preventing clogging of the bed material.

References

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**Table 4** Average influent and effluent parameters of a SFBBR plant operating on wastewater from carpet dying

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent start up phase</th>
<th>Effluent after 3 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater flow m$^3$/d</td>
<td>800–1,200</td>
<td>10–30</td>
<td>800–1,200</td>
</tr>
<tr>
<td>COD surface load g/(m$^2$.d)</td>
<td>10–30</td>
<td></td>
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<tr>
<td>COD mg/L</td>
<td>1,500–6,000</td>
<td>1,000–2,000</td>
<td>800–1,200</td>
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</table>