The application of moving bed biofilm reactor to denitrification process after trickling filters

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ABSTRACT

The paper presents research of a prototype moving bed biofilm reactor (MBBR). The device was used for the post-denitrification process and was installed at the end of a technological system consisting of a septic tank and two trickling filters. The concentrations of suspended biomass and biomass attached on the EvU Perl moving bed surface were determined. The impact of the external organic carbon concentration on the denitrification rate and efficiency of total nitrogen removal was also examined. The study showed that the greater part of the biomass was in the suspended form and only 6% of the total biomass was attached to the surface of the moving bed. Abrasion forces between carriers of the moving bed caused the fast stripping of attached microorganisms and formation of flocs. Thanks to immobilization of a small amount of biomass, the MBBR was less prone to leaching of the biomass and the occurrence of scum and swelling sludge. It was revealed that the maximum rate of denitrification was an average of 0.73 gN-NO3/gDM·d (DM: dry matter), and was achieved when the reactor was maintained in external organic carbon concentration exceeding 300 mgO2/dm3 chemical oxygen demand. The reactor proved to be an effective device enabling the increase of total nitrogen removal from 53.5% to 86.0%.

Key words | denitrification, EvU Perl, external carbon source, MBBR, nutrient removal, trickling filters

INTRODUCTION

Poland, according to the Water Framework Directive 2000/60/EC of the European Union, from year 2015 must ensure 75% removal of nitrogen and phosphorus from the municipal wastewater with respect to influent at wastewater treatment plants (WWTPs). New constructed and upgraded WWTPs serving up to 2,000 population equivalent (PE), including plants using trickling filters, in the near future should make a significant contribution to improve the quality of surface waters with respect to eutrophication in Poland. The challenge of wastewater treatment in small communities and towns up to 2,000 people requires urgent solutions. Moreover, it should be possible to remove the biogenic compounds in small WWTPs to meet the requirements under the existing directive (Zwara & Obarska-Pempkowiak 2000).

In Poland, for areas of scattered settlement, there are a number of small, individual WWTPs using trickling filters. The number of these systems is over 50,000 and is still increasing (about 7,000 new facilities are constructed each year). According to Central Statistical Office at present there are 1,636 agglomerations in Poland, where only 23 million of a total 38 million people are connected to sewerage systems (Central Statistical Office 2015). The preliminary analysis showed that denitrification in small plants occurs to a limited extent, primarily due to the large unevenness of the incoming pollutant load (Jucherski & Nastawny 2015).

The population of rural areas in recent years has been increasing. Currently, in these areas live about 50% of the population of Poland. According to the report on the state of the environment in Poland published by Main Inspectorate of Environmental Protection (Główny Inspektorat Ochrony Środowiska 2008), only 1% of the inhabitants of these areas have a benefit from individual wastewater treatment systems. This means that in the next years a significant increase in the number of local WWTPs will occur.

In small WWTPs, up to 2,000 PE, where usually reactors of activated sludge or trickling filters are used, it was previously important to remove ammonium nitrogen, because of its toxic properties. Challenges in removing aerobic forms of nitrogen (nitrite and nitrate) are still unresolved in practice (Kelly et al. 2005; Sytek-Szmeichel et al. 2016).
In the present study, the operation of an industrial scale prototype device for denitrification – moving bed biofilm reactor (MBBR), which provided an additional element of wastewater treatment after BIOCLERE® trickling filters – is described. The aim of the study was to determine the concentration of both suspended biomass and attached biomass on the moving bed filling in the reactor, and to determine the efficiency of the denitrification process rate depending on the concentration of chemical oxygen demand (COD).

MATERIAL AND METHODS

The object of the research was an MBBR. The device was added to the existing WWTP serving about 200 people in the small village of Gronowo Gorne (Poland) where BIOCLERE® trickling filters are used in a biological part of this plant. The WWTP was selected due to the presence of high nitrates concentration in the outflow. Daily wastewater flow averaged 26 m³/day. The reactor was situated at the end of the purification process as shown in Figure 1. The purpose was to carry out the post-denitrification with an external organic carbon source by adding commercial product called ‘Brennta Plus’.

The reactor consisted of a reaction chamber of 6 m³ volume and a mechanical stirrer. The construction was based on the description of the device by Rusten et al. (2006). Inside was a floating moving bed – EvU Perl carriers which filled 25% of the volume of the reactor. The EvU Perl moving bed consisted of 8 mm length and 8 mm diameter carriers in the shape of small double-sided corrugated rings. The bed was characterized by a large surface area of 700 m²/m³ and density of 0.92-0.94 g/cm³ (lighter than water). EvU Perl carriers were made of recycled polyvinyl alcohol (EvU Kielce Ltd 2014).

Additional equipment consisted of a system of electromagnetic valves capable of operating in sequential mode and measuring equipment: nitrate and redox potential (ORP) probes and a thermometer. MBBR could operate automatically. With a simple controller (Zelio®) electrical equipment inside the reactor (mechanical stirrer, pump recirculation pump electromagnetic valves and a pump of external organic carbon source) operated according to a specific algorithm. The reactor worked in three phases: recirculation, mixing and filling, similar to a sequencing batch reactor (SBR). A schematic of the developed algorithm for the reactor operation system as well as a detailed outline of the reactor and its measuring equipment are shown in Figure 2(a) and 2(b).

The dose of the external organic carbon was adjusted using a dosing pump. In automatic operation of the reactor, measurements that used three different settings of dosing time were taken. This resulted in obtaining three different values of COD inside the reactor: 300, 500 and 700 mg O₂/dm³. In a series of tests the measurements of suspended biomass and attached biomass concentration settled on plastic EvU Perl carriers were taken. Determination of settled biomass concentration required a special method to assess the number of carriers in 1 m³ and determine the differences in weight between carrier with and without biomass.

In order to determine the number of carriers in 1 m³ of moving bed reactor, around 90 pieces of random EvU Perl shapes were collected. These were boiled in water (100 °C) until complete detachment from the surface of the biofilm.
occurred. A single plastic carrier was weighed on an analytical balance to the nearest 0.0001 g. Subsequently, the average weight of a single carrier was calculated. Using the manufacturer’s (EvU Kielce Ltd) specification for the bulk density of the carriers EvU Perl (250 kg/m³), the number of carriers in 1 m³ moving bed could be calculated.

In order to determine the mass of the biomass settled on the carriers in the reactor, the exact number of 390 carriers were taken from the reactor, then were boiled in distilled water at a temperature of 100°C and divided into 39 sets (each contained 10 carriers). Each set was tied with a thin fishing line, weighed and placed in the reactor. After each series of measurements the three sets of fittings were taken and dried in a drying machine in order to obtain weight of the carriers and the dry mass of the microorganisms. From the difference, the actual weight of biomass was calculated and presented as grams of dry mass (g DM). Then, in each series of measurements carried out, the average weight of the biomass of microorganisms inhabiting the 10 carriers was calculated. The determined weight of the biomass was converted into microorganisms present in 1 m³ of bed. Grouping carriers by their shape was necessary because the weight of the biomass settled on each one was in some cases too small and therefore difficult to determine.

A test was also performed with biomass suspended in wastewater in the reactor. After each series of measurements, a sample of 1 dm³ wastewater (without carriers) was taken out and the concentration of total suspended solids was identified. The sample of wastewater was filtered under reduced pressure through a filter with a pore diameter of 0.45 mm. It was assumed that total solids deposited on the filter consisted of microorganisms, whose growth was noted in the reactor. Filter paper with the suspended solids was dried in a drying machine; then dry weight was determined, which was assumed to correspond to the biomass concentration in this study. For the calculation of the denitrification rate, the sum of the concentrations of settled and suspended biomass was used.

Cuvette tests were used to indicate COD concentration in the reactor and probes at regular intervals measured the concentration of nitrates and the ORP. All measurements were made in situ. The collected data (30 measurements) were used to calculate the speed and efficiency of the denitrification process in the reactor MBBR. All measurements were made according to APHA (1992) by standard methods. This research used the following equipment:

1. Nitrates (NO₃) – the measurement was performed using a set of WTW ION 340i meter and the nitrate probe NO800 (350 measurements).
2. COD – Macherey-Nagel Nanocolor cuvette tests were used. The absorbance measurement used a portable photometer PF-11 by the same company (80 measurements).
3. ORP – measured using a second WTW ION 340i meter and SenTix ORP probe (350 measurements).
4. The concentration of biomass – determination was carried out by gravimetric method using the Radwag MAC 50/1 moisture analyzer (150 measurements).

RESULTS AND DISCUSSION

The study indicates that the moving bed EvU Perl is not the main medium of the biomass. Carriers of the moving bed were covered with biomass, which did not exceed 6% of the biomass suspended in the wastewater. Due to the abrasion forces between the carriers, the microorganisms from the surface of the moving bed quickly passed into suspended form. The attached biomass on moving bed carriers remained stable at 0.17 kg DM/m³. The concentration of suspended biomass in the MBBR steadily increased with each passing day and became stable at 2.8 kg DM/m³. The largest growth of biomass occurred in the first 2 days of the reactor operation (Figure 3). On the first day, the adaptation phase of denitrifying bacteria in the process was noticed. During the whole experiment the sum of the concentrations of suspended and attached biomass varied in the range 2.8–3.1 kg DM/m³.

The biomass concentration resulting during the experiment was comparable to a classical activated sludge system (with pre-sedimentation) and ranged from 1.5 to 3.0 kg DM/m³ (Dymaczewski 2011). The obtained values correspond to the ranges given by Rusten et al. (1994), who showed that the concentration of biomass in a Kaldnes® moving bed is higher than in the activated sludge, and ranges from 2 to 5 kg DM/m³. Based on the results obtained by Andreottola et al. (2000), it can be concluded that there was less accumulation of biomass in the bed, which had a lower specific surface area. The comparison of biomass concentrations in different devices for denitrification and specific surface area of moving bed obtained by other authors are presented in Table 1.

The MBBR reactor in Gronowo Gorne during the starting phase was operated manually, but the sequence and duration of action was the same as in the algorithm for automatic operation. Figure 4 illustrates an example series of measurements, in which it can be observed that in the process of denitrification two substrates are removed: organic carbon (expressed as COD) and nitrate. From the start-up until the end of the phase, the rates of nitrate and COD removal as well as the amount of the biomass gradually

<table>
<thead>
<tr>
<th>Author</th>
<th>Device for denitrification</th>
<th>Specific surface area [m²/m³]</th>
<th>Biomass concentration [kg DM/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dymaczewski (2011)</td>
<td>Activated sludge reactor</td>
<td>–</td>
<td>1.5–3.0</td>
</tr>
<tr>
<td>Styka (2004)</td>
<td>SBR</td>
<td>3.0–4.0</td>
<td></td>
</tr>
<tr>
<td>Rusten et al. (1994)</td>
<td>MBBR (Kaldnes)</td>
<td>530</td>
<td>2.0–5.0</td>
</tr>
<tr>
<td>Andreottola et al. (2000)</td>
<td>MBBR (Flocor)</td>
<td>160</td>
<td>1.3–3.4</td>
</tr>
<tr>
<td>This study (2016)</td>
<td>MBBR (EvU Perl)</td>
<td>800</td>
<td>2.8–3.1</td>
</tr>
</tbody>
</table>

Table 1 | Accumulation of biomass of facilities carrying out the denitrification process

Figure 3 | Changes in the concentration of attached and suspended biomass in the MBBR during first 8 days.

Figure 4 | Changes of nitrate concentration in the MBBR with initial concentration of external organic carbon of 226 mg COD/dm³ (an example series – 5 days of start-up phase.)
increased. The rate of denitrification was determined from the quotient of the slope of the straight line joining the concentrations of nitrate (Figure 4) and concentration of total biomass (biomass attached and suspended). The biggest change in the concentration of nitrate and the nutrient (expressed as COD) occurred during the first 15 minutes (0.25 hour) from the start of the reaction.

According to the research plan, after obtaining high efficiency, the manually operated moving bed reactor was switched to automatic mode and the cycles (sequences) automatically followed each other, as shown in Figure 5(a). In periods, when the automatic filling followed, the ORP was raised from −170 mV to −100 mV, and afterwards those values decreased. Nitrate concentration increased each time when the reactor passed a filling phase and decreased, when denitrification started (mixing phase). The concentration of nitrogen varied within the range 3.0–32.0 g NO3-N/m3. The cycle began with a moment of delivery of nitrate into the reactor and duration time was about 40 minutes. This period of time was called one sequence. The sequence of the five samples of the reactor is shown in Figure 5(b).

For analysis, the points from the scope of the denitrification duration in each cycle were approximated and numbered 1–5. In the same way 15 complete cycles were performed and established for the denitrification rate (Figure 5(b)).

In terms of COD from 300 to 700 mg O2/dm3 the range of denitrification rate hardly changed (Figure 6). The reactor received the maximum rate of denitrification; after averaging the results amounted to 0.73 g NO3-N/g DM·d. In some cycles denitrification rate exceeded the value of 0.90 g NO3-N/g DM·d. The fluctuations were caused by varying the rate of wastewater flow through the reactor.

When the COD value was less than 300 mg O2/dm3 denitrification rate was inhibited (Figure 6). The reason for the inhibiting was an inadequate amount of one of the substrates – organic carbon. The second substrate, nitrate, occurred in excess and could not limit the rate of the process. Therefore, the concentration of organic carbon level needs to be kept over 300 mgO2/dm3 in order to maintain effective denitrification.

In comparison to the average rate of denitrification achieved by Brennta Plus (0.73 g NO3-N/g DM·d) similar values were obtained for ethanol by Aspegren et al. (1998) – 0.80 g NO3-N/g DM·d and Pastorelli et al. (1997) – 0.71 g NO3-N/g DM·d. Aesoy & Odegaard (1994) gained 0.57 g NO3-N/g DM·d for the hydrolysed sludge. Rusten et al. (2006) reached a much higher denitrification rate such as 1.28 g NO3-N/g DM·d (for ethanol), and a very small rate for organic matter present was obtained by of Isaacs et al. (1995) – 0.02 g NO3-N/g DM·d.

Using the such designed MBBR, efficient denitrification can be occur in the effluent after a biological step. When the concentration of the total biomass in the reactor is about 3 g dm/dm3 and the COD value is more than 300 mg O2/dm3 the device is capable of removing 110 mg NO3-N in 1 hour.

Expanding the WWTP based on trickling filters in Gronowo Gorne brought the expected environmental effect. Previously, the plant discharged wastewater with about 18 mg NH4+ -N/dm3 and 37 mg NO3-N/dm3. After joining the MBBR to the technological system and after a period of adaptation of the biomass, the effluent did not exceed 6 mg
NH₄⁺-N/dm³ and 6 mg NO₃-N/dm³. Total nitrogen removal efficiency increased from 53.5% to 86.0%.

In this study, a relatively high efficiency of total nitrogen removal was achieved. Comparing this value with other methods used to carry out denitrification, it can be concluded that the effectiveness of the process depends not only on the reactor type, but also on its location in the technological system. The process was most efficient (at 85–90%), when the denitrification was performed simultaneously or at the end of the system with the addition of external organic carbon source. Less effective is the method with pre-denitrification and SBR reactors. Comparison of total nitrogen removal efficiency obtained by other authors for different examples of the denitrification process is given in Table 2.

An advantage of the investigated reactor is an ability to freely set the time of all operation phases. Changing the filling time allows customizing of the MBBR operation to the current wastewater flow, and changing the mixing time can respond to changes in the amount of nitrate which is to be removed. The concentration of the dose of external organic carbon can also be set arbitrarily. The design of the system allows control of all aspects of the process, making it easier for the operators of the WWTPs.

Comparing the MBBR to SBR it can be concluded that they are very similar devices. Both devices have the possibility of changing the phase and allow good control of denitrification and other processes in wastewater treatment. However, the essential element that differentiates these two devices is the presence of the moving bed. The possibility to change the degree of filling of the MBBR by EvU Perl carriers makes the technology more flexible. Another benefit is the immobilization of a small quantity of biomass on the carrier surface. Despite the fact that the amount of attached biomass is only 6% of the total biomass, it is very active, which was visually observed during the study. Intense shearing forces between the carriers make the microorganisms detach from the surface of media and form flocs among the EvU Perl filling. This is therefore a proof that attached and suspended biomass are located in one reaction volume and more nitrates can be removed per hour. In this aspect, the MBBR has an advantage over SBR and other techniques used in the wastewater purification. This explains why in recent years very often the existing WWTPs are adapted to increasing loads by adding MBBRs to activated sludge systems. Moreover, the MBBR reactors can be used to remove large concentrations of contaminants, for the treatment of

<table>
<thead>
<tr>
<th>Author</th>
<th>Description of the process</th>
<th>% of removed total nitrogen</th>
</tr>
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<tbody>
<tr>
<td>Rusten et al. (1994)</td>
<td>Pre-denitrification (MBBR)</td>
<td>45</td>
</tr>
<tr>
<td>Odegaard et al. (1999)</td>
<td>Simultaneous denitrification (MBBR)</td>
<td>70</td>
</tr>
<tr>
<td>Podlewna &amp; Zubrowska-Sudol (2001)</td>
<td>Simultaneous denitrification (SBR)</td>
<td>75</td>
</tr>
<tr>
<td>Helness &amp; Gisvold (2001)</td>
<td>Simultaneous denitrification (MBBR)</td>
<td>80</td>
</tr>
<tr>
<td>Kaldnes Miljoteknologi (2002)</td>
<td>Pre-denitrification (MBBR)</td>
<td>85</td>
</tr>
<tr>
<td>Odegaard (2005)</td>
<td>Pre-denitrification (MBBR)</td>
<td>65</td>
</tr>
<tr>
<td>Helness &amp; Odegaard (2005)</td>
<td>Simultaneous denitrification (SBR)</td>
<td>59</td>
</tr>
<tr>
<td>Cema et al. (2005)</td>
<td>Simultaneous denitrification (anammox)</td>
<td>88</td>
</tr>
<tr>
<td>Bernat et al. (2005)</td>
<td>Simultaneous denitrification (SBR)</td>
<td>70</td>
</tr>
<tr>
<td>Makowska (2002)</td>
<td>Simultaneous denitrification (MBBR)</td>
<td>75</td>
</tr>
<tr>
<td>Dymaczewski (2011)</td>
<td>Simultaneous denitrification (activated sludge)</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Simultaneous denitrification (activated sludge + anammox)</td>
<td>80</td>
</tr>
<tr>
<td>This study (2016)</td>
<td>Post-denitrification (MBBR)</td>
<td>86</td>
</tr>
</tbody>
</table>
leachate from municipal sludge dewatering or industrial wastewater (Weiss et al. 2005).

In the study, the detachment of the biofilm from carriers and its transition in the relaxed form were observed, but demonstration of the microorganism species composition in both types of biomass and their layered stratification requires additional, more complex research (Almstrand et al. 2014).

Due to the fact that floating filling is mixed by the stirrer in the entire volume of the MBBR and it has frequent contact with the surface of wastewater, there is less risk of swelling and scum than in the case of the SBR. The fixing biofilm makes the intense recirculation of wastewater not important and the reactor less prone to leaching the biomass, (for example, during intense flows of wastewater or electrical power supply failure). This is especially important in areas of scattered settlement (Gajewska et al. 2011).

CONCLUSIONS

Evaluating the effect of the MBBR, it could be noted that the device is capable to gain the efficient denitrification at high rate and efficiency of 86%.

The device can be used in small WWTPs based on the technology of trickling filters but also it can work in large plants as an additional device to remove nitrates. The study achieved a relatively high denitrification rate averaging 0.73 g NO₃-N/gDM·d and proved that the process takes place efficiently when the MBBR is maintained at a concentration of organic carbon over 300 mgO₂/dm³.

Studies have shown that the EvU Perl moving bed is not the main carrier of biomass. Only 6% of the total biomass is attached to the carrier surface. EvU Perl filling, due to the forces of abrasion, cause rapid breaking up of biofilm and fast formation of flocs. As a result, the moving bed take an active part in the fast increase of biomass in the reactor.

The presented reactor is easy to use and with a suitable control system can be adapted to changing concentrations and flows. The high efficiency of denitrification can be achieved, which has been evidenced by this study and other authors’ research.

Assessing the MBBR reactor in terms of the use of small plants in scattered settlements, it is a device that could prevent the ingress of oxygen forms of nitrogen to surface waters, and thus contribute to improving their quality.

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First received 5 December 2015; accepted in revised form 20 September 2016. Available online 8 October 2016