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NITROGEN REDUCTION AT FIVE SWEDISH MUNICIPAL WASTEWATER TREATMENT PLANTS CONFIGURED IN A MULTI-REACTOR MOVING BED BIOFILM REACTOR PROCESS

Kvävereduktion på fem kommunala avloppsreningsverk i Sverige som tillämpar hela processen med rörliga bärare

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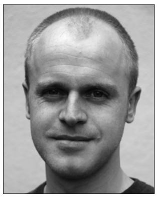

Abstract

Results from wastewater treatment plants with their entire biological treatment step in a multi-reactor configured Moving Bed Biofilm Reactor process designed for nitrogen reduction is available on at least five places in Sweden. An evaluation has been made; of the design and reduction efficiency from these five wastewater treatment plants. The study confirms the idea that these Moving Bed Biofilm Reactors have been constructed in small volumes. However the treatment results have in some cases not been satisfactory. Among the five treatment plants, only one shows good performance. The reactor set up and the small volumes can therefore be attributed to overestimation of the capacity or the necessity to make the technology competitive.

Key words – Moving Bed Biofilm Reactor, Nitrogen reduction, Full-scale experiences, Design, Sweden

Sammanfattning

Resultat från avloppsreningsverk som har hela det biologiska reningssteget i en flerstegs process bestående av rörlig biofilm (**M**oving **B**ed **B**iofilm **R**eactor) dimensionerad för kvävereduktion finns på åtminstone fem reningsverk i Sverige. Dessa fem avloppsreningsverk har utvärderats med hänsyn till design och effektivitet i denna studie. Studien bekräftar uppfattningen om att reningsverk med rörlig biofilm har konstruerats med små volymer. Dock har reningsresultaten inte alltid visat sig vara tillfredställande. Bland de fem, uppvisar endast ett reningsverk tillfredsställande resultat, i synnerhet med avseende på kvävereningen. Processtrukturen och de små volymerna kan därmed vara ett tecken på att kapaciteten överskattas eller att det finns ett behov av att dimensionera snålt för att göra tekniken konkurrenskraftig.

Introduction

Biofilm processes, as Conventional Trickling Filters (CTF) are constructed in smaller volumes than suspended processes as Conventional Activated Sludge (CAS) systems. They are known for being less sensitive for hydraulic variations and have displayed good reduction results of organic compounds but less respectable nitrogen reduction capacity. Several pilot and full-scale studies of multi-reactor sequenced Moving Bed Biofilm Reactor (MBBR) systems where carried out in the 90's. Among those Ødegaard and Rusten (1994) and Rusten and Hem (1995a) indicated problems in establishing good denitrifaction in pre-denitification mode and limited removal efficiency. Both pre- and post denitrification were studied intensely during the 90s at full-scale plants in Norway. Testing and start-up of the nine reactors sequenced Lillehammer Waste Water Treatment Plant (WWTP) is described by Rusten and Siljudalen (1995). Results at Lillehammer included over 80 % nitrogen reduction in 1995. Gardemoen WWTP was studied by Tranum and Rusten (1999) with excellent results, reaching 90 % reduction of nitrogen in a sequence of seven reactors. The plant was revaluated by Rusten and Wien (2000) and the plant had a capacity of exceeding 85 % total nitrogen reduction efficiency.

In five municipalities in Sweden, MBBR processes are used over the entire biological treatment step for nitrogen reduction. Three of them have a configuration of pre-denitrification and two have both pre- and post-denitrification. The WWTPs are small compared with conventional systems and four of them are having capacity problems. This paper has its focus on evaluating full scale MBBR installations in Sweden with two different processes and their nitrogen reduction capacity.

Theory

In theory, pre-denitrification capacity is limited by hydraulics and very dependent on the recirculation ratio. Praxis for recirculation ratio for CAS has been three times the influent flow besides the nitrate containing sludge recycle stream. It is however not unusual that the recirculation ratio is higher than three in CAS processes – particularly since a full scale plant average flow seldom are the design flow for pumps etc. The nitrate reduction potential depends on the recirculation ratio according to equation [1] described by Ødegaard (1992).

$$R_N(\%) = \frac{r}{r+1} * (100\,\%) \qquad [1]$$

The relation between recirculation ratio and the potential reduction of nitrate from equation [1] is visualised in Figure 1. It implies that a recirculation ratio of 2 results in a maximum theoretical nitrate reduction of around 66 %.

As seen in Figure 1, the potential reduction of nitrate increase with increasing recirculation ratio. Rusten and Hem (1995a) however displayed that there was a decrease in nitrogen reduction in MBBR processes when the recirculation ratio exceeded two. The reduced denitrification performance was elucidated by Rusten and Hem (1995a) as large amounts Dissolved Oxygen (DO) being returned to the denitrification step and dilution of the influent easily degradable carbon (SBOD) for denitrification. Since MBBR processes operates under higher DO concentrations, in the range of 5 to 8 mg per L, deoxidation is crucial for the process, and utterly problematic. Pre-denitrification in a MBBR process is therefore an issue of higher DO concentrations and recirculation ratios than for corresponding CAS processes, to achieve the same nitrate reduction potential. The capacity is therefore not only an issue of dilution sensitive degradation rates, but hydraulics in a complex feedback system. There are also hydraulic limitations due to the presens of carriers and sieves and reduction limitations are rapidly reached in the system.

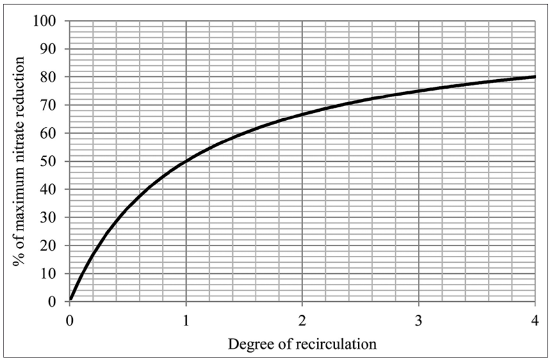

Figure 1. *Potential nitrated reduction in relation to the recirculation ratio.*

Substantial nitrification is considered crucial for a high nitrogen reduction capacity in multi-reactor configured MBBR processes and Rusten and Hem (1995a) suggested that nitrification rates could be described as reduction of ammonium per area biofilm and can be estimated according to equation [2].

$$r_{A,\,NH_4} = k_A * S_n{}^N \qquad [2]$$

Where r_{A,NH_4} is the ammonium degradation rate in the biofilm per unit area and depends on a temperature sensitive reaction rate coefficient and a rate limiting substrate concentration. The rate limited substrate concentration for nitrification is estimated in each of the individual aerated reactor, connected in series. The substrate concentration S_n is limited by either oxygen concentrations S_O available in the biofilm or the Total Ammonium Nitrogen (TAN) concentration in the wastewater, denoted S_A and finally adjusted to a reaction order N estimated to 0.7 according to Hem and Rusten (1994) and Rusten *et al.* (2006). Oxygen rate limited conditions S_O can be described according to Simonsen (2008), seen in equation [3].

$$S_O = \frac{DO_{DIM} - DO_{DEP}}{\left(\frac{DO}{TAN}\right)_{TRANS}} \qquad [3]$$

Where DO_{DIM} is the oxygen concentration in the bulk phase of the selected design and DO_{DEP} is the estimated consumption of oxygen through the heterotrophic layer of the biofilm, estimated to be 0.5 mg DO per L for very low BOD_5 concentrations and up to 2.5 mg DO per L for $SBOD_5$ close to 1.5 mg per L according to Rusten and Hem (1995a). The transition $\left(\frac{DO}{TAN}\right)_{TRANS}$ between oxygen rate limited nitrification and ammonium

Table 1. *Design and dimensions of the five studied WWTPs.*

WWTP	PE_{DIM}	PE_{LOAD}	PE_{DIM}/ PE_{LOAD}	Volume tot	Volume ox	Part ox	PE_{DIM}/ tot m^3	PE_{DIM}/ ox m^3	Steps (Reactors) [Lines]
	PE	PE	%	m^3	m^3	%	PE/m^3	PE/m^3	
Pre-den.									
Brandholmen	50 000	45 000	90	3 660	1 960	53.6	13.7	25.5	5,(5),[2]
Ulricehamn	12 500	10 000	80	1 100	730	66.4	11.4	17.1	4,(3),[1]
Åmål	13 500	3 500	37	800	530	66.3	16.9	25.5	5,(4),[1]
Pre-and Post-den.									
Margretelund	40 000	21 900	55	2 750	1 925	70.6	14.5	20.8	4,(4),[2,3]
Visby	60 000	42 688	71	5 800	2 500	43.0	10.3	24.0	9,(9),[1]

rate limited nitrification is between 2.5 and 4 mg per L according to Rusten and Hem (1995a) and often set to 3.2, specified by Szwerinski and Arvin (1986). The value is valid when easy degradable organic compounds are absent. The reaction rate coefficient depends on the temperature under oxygen rate limited nitrification according to equation [4], described by Rusten *et al.* (2006).

$$k_{T_2} = k_{T_1} * \theta_T^{(T_2 - T_1)} \qquad [4]$$

Where k_{T_2} and k_{T_1} is the reaction rate constant at different temperatures and θ_T describes the temperature coefficient, set to 1.06 by Ødegaard (1992) and 1.09 by Rusten and Hem (1995b). The rate coefficient k_{T_2} is decreasing with increasing soluble organic loads (SBOD) and suspended matter in the wastewater described by Rusten *et al.* (2006). At low ammonium concentrations k_A is estimated to 0.5 d^{-1} according to Rusten *et al.* (2006). Therefore, it is implied that high oxygen concentrations and high temperatures, with low concentrations of soluble BOD and Total Suspended Solids (TSS) are necessary for high nitrification rates in well-established nitrifying biofilms.

Methodology

There are five known WWTPs with MBBR processes in Sweden that is studied in this paper with results from 2010. The five WWTPs have been assessed by contacting the WWTPs and by evaluating results from Environmental reports submitted to the Swedish EPA. Design and volumes can be seen in Table 1, notice that the key figure Person Equivalents (PE), is defined as 70 gram BOD_7 per person and day in Sweden.

WWTP with pre-denitrification

Brandholmens WWTP (1998) is designed for 50 000 PE and located south west of Stockholm, is configured as pre-denitrification. The biological step is separated in two parallel lines with two reactors for pre-denitrification, two aerated reactor for oxidation and finally a deoxidation reactor. The WWTP has a nitrogen demand of 15 mg per L which the treatment plant fails to reach.

Ulricehamns WWTP (2007) is designed for 12 500 PE and located in the southern province of Västergötland and is configured as pre-denitrification. The MBBR process is constructed in an old CTF reactor which is compartmentalized in to one anoxic reactor and two aerated reactors, and finally a carrier free deoxidation reactor. There is a possibility to feed the anoxic reactor with ethanol. The entrepreneur guaranty is 16 mg total nitrogen effluent, which the WWTP fails to reach.

Åmåls WWTP (2008) is designed for 13 500 PE and located close to the southern Norwegian boarder, northwest of the lake Vänern and is configured as pre-denitrification. The MBBR process is constructed in two old CAS reactors and compartmentalized in one anoxic reactor, three aerobic reactors and finally a small carrier free deoxidation reactor. The WWTP has no nitrogen effluent demands but the plant is designed to reach 15 mg per L which it with a nitrogen reduction of 41 %, barely achieved in 2010.

WWTP with both pre- and post-denitrification

Margretelunds WWTP (1999) is designed for 40 000 PE and located northeast of Stockholm. The MBBR process is configured as both pre- and post-denitrification. The WWTP is divided in two separate lines for the first anoxic reactor and first aerated reactor and in three parallel lines for the second aerated reactors. The post-denitrification consists of three parallel lines. The demand of the WWTP is 15 mg per L and the WWTP reached 15 mg per L according to the environmental report.

Visby WWTP (2007) is designed for 60 000 PE and situated on the Baltic island of Gotland and is configured as both pre- and post-denitrification. The process

Table 2. *Capacity of the five WWTP with MBBR processes.*

WWTP	BOD_{DIM} kg/day	BOD_{LOAD} kg/day	N_{LOAD} kg/day	$N_{EFFL.}$ kg/day	N_{RED} kg/day	BOD_{LOAD}/N_{RED} kg/kg	BOD_{LOAD}/ox m^3 kg/m^3	m^3/N_{RED} m^3/kg
Pre-den.								
Brandholmen	3 500	3 150	576.2	290.1	286.0	11.0	1.61	12.8
Ulricehamn	875	700	155.0	78.7	76.3	9.2	0.96	14.4
Åmål	945	245	95.2	59.0	36.2	6.7	0.46	21.9
Pre-and Post-den.								
Margretelund	2 800	1 530	338.0	124.0	214.0	7.2	1.45	12.9
Visby	4 200	2 990	526.7	129.0	397.7	7.5	1.20	14.6

consists of a sequence of nine deep reactors connected in series with two anoxic reactors, four aerated reactors, one deoxidation reactor and finally two external carbon-fed anoxic reactors. The WWTP is unevenly loaded throughout the year and have high loads during the summer period. The demand of the WWTP is 15 mg per L which the plant accomplished with margins.

Results

The results of the study can be seen in Table 2 and Table 3 and are mainly based on results from environmental reports. The relationship between BOD_7 and BOD_5 can be estimated according to Rusten and Kolkinn (1997) as equation [5].

$$BOD_7 = 1.15 * BOD_5 \quad [5]$$

It is important to remember that all the treatment plants are designed for the effluent demand 15 mg per L except for Ulricehamn, which for some reason is designed for an effluent concentration of 16 mg per L total nitrogen. However, neither Ulricehamn WWTP nor Åmål WWTP had a nitrogen demands from governing authorities in 2010.

Treatment results in Table 3 shows capacity problems at four WWTPs that do not reach or reaching nitrogen demands, guarantees and/or design specifications without margins, despite not being fully loaded. Visby WWTP performs so far well with sufficient nitrogen reduction and stable and substantial nitrification. Table 3 shows that full reduction of ammonium, by oxidation and assimilation is achieved at least at two WWTP with MBBR processes. The three WWTP with pre-denitrification do not reach a reduction exceeding 50 % of total nitrogen influent. Neither Brandholmens WWTP reach its 15 mg per L total nitrogen effluent demand nor has Ulricehamn WWTP ever reached its 16 mg per L total nitrogen effluent guarantee. The three WWTPs Ulricehamn, Åmål and Margretelund, do not reach complete reduction of ammonium on a yearly basis and all three have capacity problems. Differences in reduction capacity can be seen within pre denitrification and pre- and post denitrification at Brandholmen and Visby WWTPs. Visby is the only treatment plant that reaches a higher reduction, which for the moment exceeds 75 %, and it is likely that it can achieve even more than that. It is though not needed for this plant since it is reaching its 15 mg per L demand with margins. Energy consumption is an important part of the operational costs of a

Table 3. *Treatment results for the five WWTP with MBBR processes.*

WWTP	NH_4-N Infl. mg/L	NH_4-N Effl. mg/L	NH_4-N_{RED} %	N Infl. mg/L	N Effl. mg/L	N_{RED} %	N_{RED}/m^3 g/m^3	PE_{DIM}/N_{RED} PE/kg	PE_{LOAD}/N_{RED} PE/kg
Pre-den.									
Brandholmen	30.2	2.7	91.1	39.7	20.0	49.6	79.4	174.8	157.3
Ulricehamn	28.2	13.8	51.1	39.0	20.0	48.7	69.4	163.8	131.1
Åmål	15.5	8.9	42.6	25.6	15.1	41.0	45.6	369.8	95.9
Pre- and Post-den.									
Margretelund	u.i	8.2	u.i	43.0	15.9	63.0	77.8	186.9	102.3
Visby	30.0	0.7	97.7	49.0	12.0	75.5	71.6	150.9	107.3

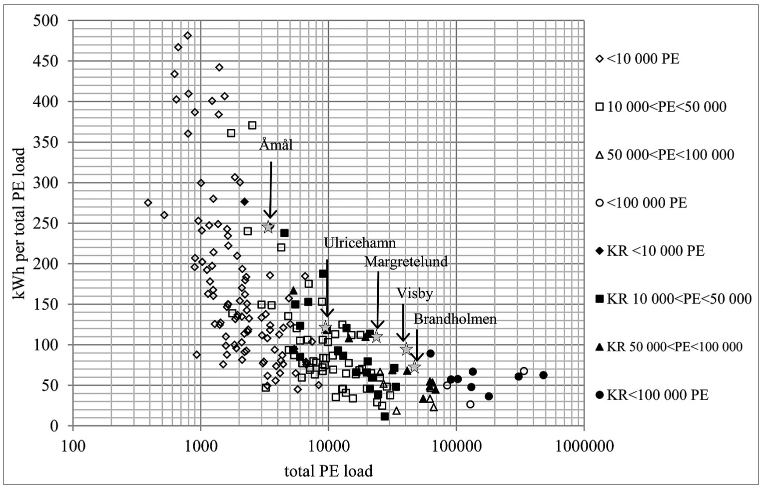

Figure 2. *Energy use at more than 300 WWTP in Sweden, where the five WWTP with MBBR processes is marked with a star. WWTP marked as KR had nitrogen reduction demands introduced in 2007 or earlier. The data comes from the year 2009.*

WWTP. The energy use in 2009 at over 300 Swedish WWTPs can be seen in Figure 2. The WWTPs are grouped in four different sizes and separated into WWTPs with no nitrogen reduction and WWTP with nitrogen reduction (KR). The five WWTPs with nitrogen reduction in MBBR processes is marked with stars and are labelled.

As can be seen in Figure 3, the influent nitrogen load at Visby WWTP varies intensely with a large standard deviation. An indication of a decline in influent concentrations can be seen towards the end of the year. The effluent nitrogen concentration has a considerable smaller variation.

Discussion

Due to absence of standardised design guidelines and directions for construction, the design of biological wastewater processes in Sweden is an issue of pragmatism and individual preferences. There are differences between different processes that have to be considered in the design and construction of the MBBR systems and that differs utterly from conventional activated sludge systems. Among those, the multi-reactor set up of reactors in series. It is therefore reasonable to say that not all MBBR processes in this study have been constructed in a way that is optimal for the technique. The key figures in Table 1 and Table 2 which displays design and performances of the treatment systems should therefore be interpreted with precaution. Based on results found in Table 3, pre-denitrification has a low nitrogen reduction which is in compliance with results found by Rusten and Hem (1995). The theoretical dilemma with the process and the limitations of the treatment process is externalized in results displayed in Table 3 and independent of the load on the treatment plant, seen in Table 1. As the theory in Figure 1 depicts, a rising nitrate reduction potential follows by an increasing recirculation ratio. However, high recirculation ratios will recirculate too much

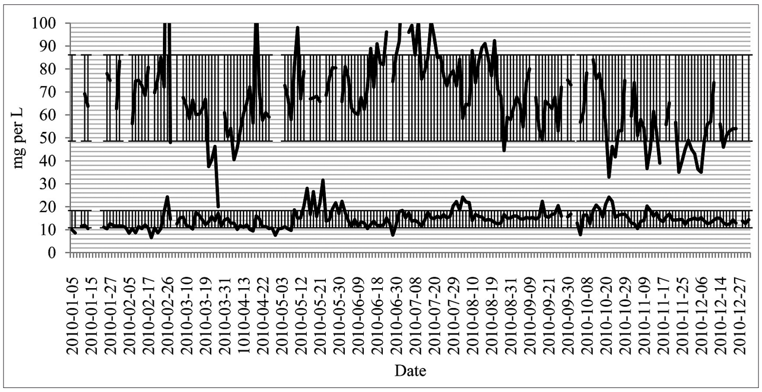

Figure 3. *The influent and effluent nitrogen concentrations to the MBBR process at the Visby WWTP in 2010.*

oxygen to the anoxic reactor, reducing hydraulic retention times and dilute influent concentrations of substrate. Hydraulic properties for carriers and sieves, limits the flows through the reactor. Degradation rates in MBBR reactors have been through the years a moot point in which construction is based upon, but not particularly applicable in design of pre-denitrification processes. The two wastewater treatment plant with both pre- and post-denitrification, can be seen in Table 3, having a nitrogen reduction exceeding 60 %. The substantial differences between pre- and post-denitrification is the ability to reduce high oxygen levels with addition of external carbon source and longer resident times. Indications on the importance of substantial nitrification as a key component for high nitrogen reduction can be seen in Table 3. As seen in Table 3, both Brandholmen and Visby WWTP reach significant nitrification. Brandholmens WWTP can't however denitrify sufficient amount of nitrate to reach demands due to the limitations of the pre-denitrification process. At Visby WWTP, that problem is resolved by addition of external carbon, in the post-denitrification step. As can be seen in Figure 3, the effluent nitrogen concentrations have a lower variation in the data set, indicating a fairly controllable process. After the nitrification process, a deficiency of reduced substrate for the biomass to oxidise occurs. To compensate for this an addition of external carbon is necessary, both for deoxidation and the following denitrification. Without this addition less biomass will be present in the deoxidation reactor and hence less consumption of oxygen will take place. Visby WWTP reaches, therefore a respectable performance due to the multi-reactor set up in series that enables substantial nitrification. The addition of external carbon provides an environment suitable for post-denitrification. As can be seen in Figure 2, the WWTPs with MBBR processes does not stand out too much from the other WWTPs but they are not energy efficient despite the fact that they are fairly new constructions.

Conclusion

Nitrogen reduction in a MBBR processes, involves a multi-reactor configuration set up. Pre-denitrification requires higher recirculation ratio in smaller volumes and a higher oxygen concentration in the aerated reactors than in corresponding CAS processes. Therefore limited nitrogen reduction is to be expected which could lead to difficulties in reaching nitrogen demands. Observations on the three present WWTPs are confirming expectations and the theoretical predictions. WWTPs configured with both pre- and post-denitrification in MBBR process indicates that post-denitrification can compensate for high oxygen levels by addition of external carbon if nitrification is sufficient. This study confirms the idea that MBBR processes are indeed constructed in small volumes. However the treatment results are unsatisfactory for four WWTPs and can be attributed to overestimation of the capacity.

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