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The Moving Bed Biofilm Reactor

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Abstract

A new biofilm reactor for wastewater treatment, the moving bed biofilm reactor (MBBR), is discussed. A general description of the reactor is given. Results from investigations of different applications (carbonaceous removal, nitrification and nitrogen removal) when used for municipal wastewater treatment, are discussed. Design values are given and it is demonstrated that use of this reactor results in very compact treatment plants .

Keywords : Wastewater, biological treatment, biofilm reactor

INTRODUCTION

Over the last decades there has been a growing interest in biofilm processes for wastewater treatment. There are several reasons for the fact that biofilm processes more and more often are being favoured instead of activated sludge processes, such as :

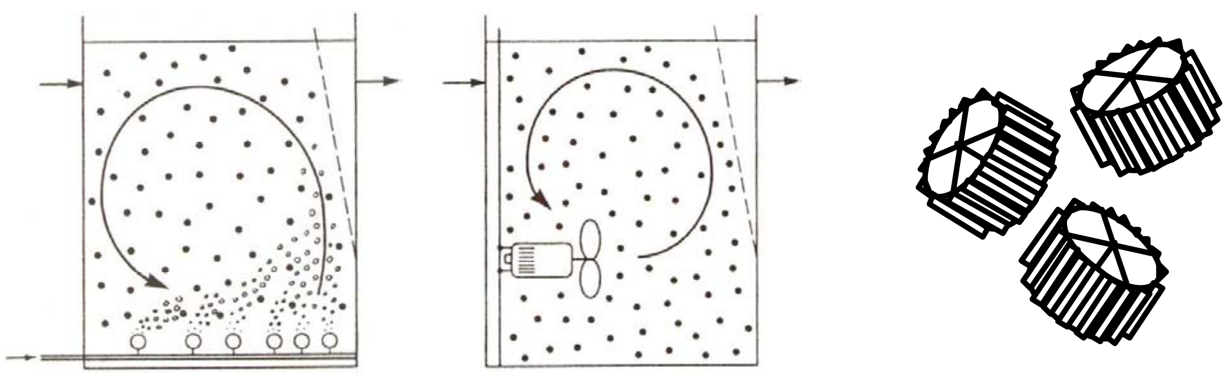
a. The treatment plant requires less space
b. The final treatment result is less dependent on biomass separation since the biomass concentration to be separated is at least 10 times lower
c. The attached biomass becomes more specialised (higher concentration of relevant organisms) at a given point in the process train, because there is no sludge return

There are already many different biofilm systems in use, such as trickling filters, rotating biological contactors (RBC), fixed media submerged biofilters, granular media biofilters, fluidised bed reactors etc. They have all their advantages and disadvantages. The trickling filter is not volume-effective. Mechanical failures are often experienced with the RBC's. It is difficult to get even distribution of the load on the whole carrier surface in fixed media submerged biofilters. The granular media biofilters have to be operated discontinuously because of the need for backwashing and the fluidised bed reactors show hydraulic instability. For these reasons the moving bed biofilm process (Eur. pat. no. 0575314, US pat. no. 5,458,779) has been developed in Norway during the last 10 years (Ødegaard et al, 1994, Ødegaard et al, 1998a).

There are presently more than 90 treatment plants based on this process in operation or under construction in 17 different countries all over the world. They are used for many different purposes for municipal as well as industrial wastewater treatment, like organic matter removal, nitrification and nitrogen removal. In this paper we shall focus on the municipal applications.

DESCRIPTION OF THE MOVING BED BIOFILM REACTOR (MBBR)

The idea behind the development of the moving bed biofilm process was to adopt the best from both the activated sludge process and the biofilter processes without including the worst. Contrary to most biofilm reactors, the moving bed biofilm reactor utilises the whole tank volume for biomass growth, as does also the activated sludge reactor. Contrary to the activated sludge reactor, it does not need any sludge recycle, as is also the case in other biofilm reactors. This is achieved by having the biomass grow on carriers that move freely in the water volume of the reactor, kept within the reactor volume by a sieve arrangement at the reactor outlet. Since no sludge recirculation takes place, only the surplus biomass has to be separated - a considerable advantage over the activated sludge process. The reactor may be used for both aerobic, anoxic or anaerobic processes, see figure 1.



a. Aerobic reactor   b. Anoxic and anaerobic reactor   c. The biofilm carrier (K1)

Fig. 1. The principle of the moving bed biofilm reactor and the shape of the biofilm carrier

In aerobic processes, the biofilm carrier movement is caused by the agitation set up by the air, while in anoxic and anaerobic processes a mixer (normally a horizontal shaft mounted banana mixer) keeps the carriers moving. In the aerobic reactors a special coarse bubble aeration system has been developed. The carriers are kept within the reactor by an outlet sieve. Most of the plants are designed with vertically mounted, rectangular mesh sieves, but it is sometimes shaped as a cylindrical bar sieve, vertically or horizontally mounted. The biofilm carrier (K1) is made of high density polyethylene (density 0,95 g/cm^3) and shaped as a small cylinder with a cross on the inside of the cylinder and “fins” on the outside (see figure 1c). The cylinder has a length of 7 mm, and a diameter of 10 mm (not including fins). Lately one has introduced also a larger carrier (K2) of similar shape (length and diameter about 15 mm), intended for use in plants with coarse inlet sieves.

One of the important advantages of the moving bed biofilm reactor is that the filling of carrier in the reactor may be subject to preferences. The standard filling degree is 67 %, resulting in a total, specific carrier area of 465 m^2/m^3. Since the biomass is growing primarily on the inside of the carrier, one is calculating with an effective specific surface area of 335 m^2/m^3 for the K1 carrier and 235 m^2/m^3 for the larger K2 carrier, at 67 % filling. In order to be able to move the carrier suspension freely it is recommended that filling degrees should be below 70 % (corresponding to 350 m^2/m^3 effective specific area for K1). One may, however, use as much as needed below this, which is convenient, especially when upgrading plants – for instance from activated sludge to moving bed reactors.

The rate expression normally used in biofilm processes is based on biofilm carrier area (g/m^2d). Because of some uncertainty with respect to how much of the available carrier area that is in fact covered by biofilm and because of easy rate comparison with other biofilters, the volumetric rates ($g/m^3_{reactor\ volume}d$) have been used earlier for the moving bed reactor. It has been demonstrated, however, that the biofilm area is the key parameter and therefore the design of the process is most correctly based on effective carrier area ($g/m^2_{carrier\ area}d$) (Ødegaard et al, 1998b).

As in every biofilm process, diffusion of compounds in and out of the biofilm plays a key role. Because of the importance of diffusion, the thickness of the effective biofilm (the depth of the biofilm to which the substrates have penetrated) is significant. Since this depth of full substrate penetration is normally less than 100 μm, the ideal biofilm in the moving bed process is thin and evenly distributed over the surface of the carrier. In order to obtain this, the turbulence in the reactor is of importance, both in order to transport the substrates to the biofilm and to maintain a low thickness of the biofilm by shearing forces. Various investigations have shown that the typical biomass concentration when calculated on reactor volume, is in the order of 3-4 kg SS/m^3, about the same as in activated sludge reactors. Since the volumetric removal rate is several times higher in the moving bed process, this can only mean that the biomass of this process is much more viable.

Fig 2. Photo of a Kaldnes moving bed reactor

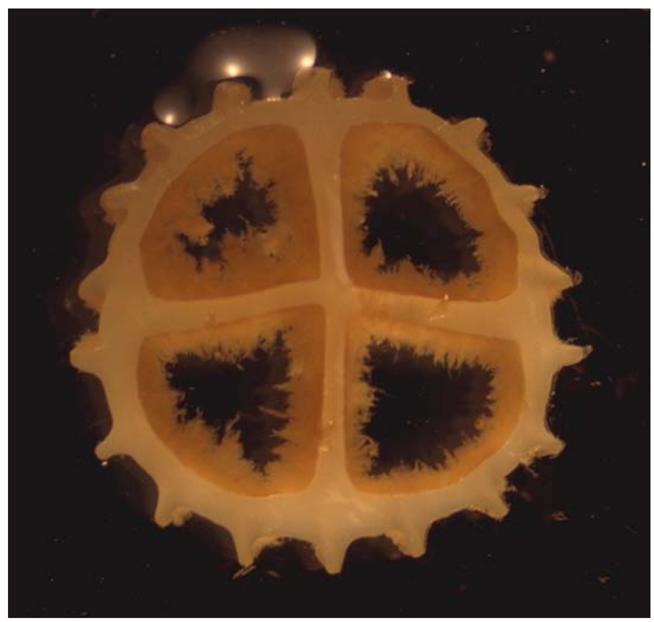


Fig. 3 Photo of a KMT K1 carrier under water

In cases where the turbulence is too low, shearing of the biofilm may be inadequate and more biomass than wanted may establish itself in voids of the carrier (see figure 3), thus restricting free passage of water and substrates to the biofilm. When the turbulence is adequate (either caused by aeration or mixing), the biofilm is thin and smoothly covering the inside area of the cylindrical carrier. As demonstrated in figure 3, much less biomass is growing on the outside of the carriers than on the inside. This is probably caused by the fact that abrasion is limiting growth when carriers are colliding.

With an activated sludge plant, the process of developing an active biomass begins with the growth of zoogleal bacterial flocs which then becomes colonised by protozoa which feed on the free swimming bacteria to produce a clarified effluent. In the moving bed process, the order of colonisation seems to be reversed (Mosey, 1996). High loading rates, around 30 g COD/m^{2}d, produce compact bacterial biofilms, with protozoan population either absent or limited to small free-swimming protozoa and Vorticella spp. Moderate loading rates, around 10-15 g COD/m^{2}d promote a more "fluffy" biofilm with a rich variety of ciliated protozoa. Low loading rates (< 5 g COD/m^{2}d) promote very "fluffy biofilm generally dominated by stalked ciliates.

THE MOVING BED BIOFILM PROCESSES

The moving bed biofilm process has been used for many different applications. It was developed at the time when nitrogen removal became in focus and most of the scientific data has been gathered from this application. Later, however, organic matter removal has been more investigated, including high-rate pre-treatment for upgrading of activated sludge plants. At the time research is being conducted in order to evaluate the process for biological phosphate removal. The process has been used both for municipal wastewater and industrial wastewater (mainly foodstuff industries and pulp and paper industries). Here we shall focus on municipal wastewater. In figure 4 some common flow diagrams for different applications are presented and we shall use these diagrams as the basis for discussing results and experiences with the moving bed process so far.

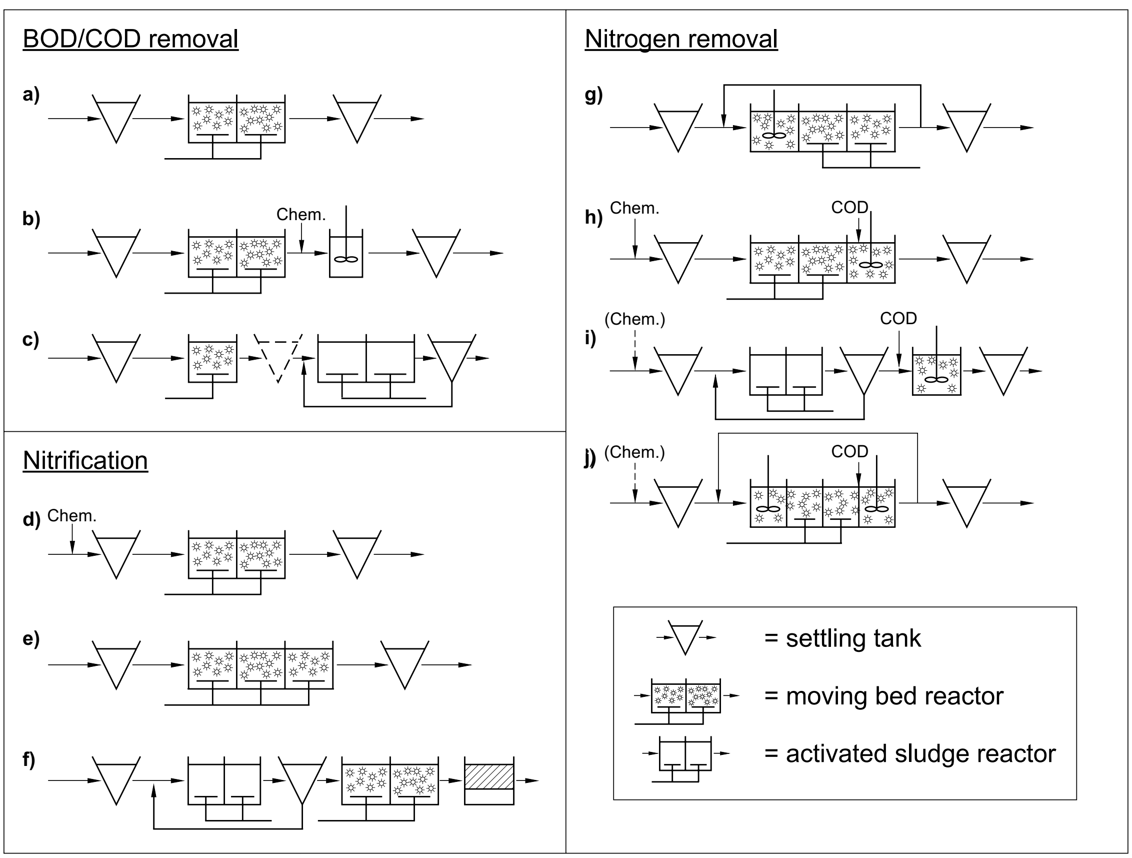


Fig. 4 Typical moving bed biofilm process flow diagrams for different applications

Pre-settling is normally used as pre-treatment primarily to avoid clogging of the bio-reactor sieves. Pre-settling is not a prerequisite, however, but very often useful because it adds flexibility, for instance by allowing pre-coagulation. As mentioned above a new larger carrier (K2) is now being introduced allowing larger bio-reactor sieve openings and no pre-settling tank.

SECONDARY TREATMENT

BOD/COD removal only (see figure 4a)

For secondary treatment only, the process has normally been designed for a volumetric loading of 4-5 kg BOD_7/m^3d at 67 % carrier filling (335 m^2/m^3) and 15^oC. This is corresponding to a loading based on area of ca 15 g BOD_7/m^2d, which is somewhat higher than what RBC-processes have been designed for the same purpose. In Scandinavia there are not many of these plants since phosphate removal is always required. The process for high-rate BOD/COD-removal has, however, been evaluated, especially as a first-step process in a two-step system.

Because of the compactness of the process, the residence time in Kaldnes-reactors for carbonaceous matter removal will be quite low (30-90 minutes), depending on the organic load and the strength of the wastewater. Biodegradable, soluble organic matter is quickly degraded. Particulate organic matter is partly caught by the irregularities of the attached biomass, hydrolysed and degraded, and partly it passes more or less unchanged through the reactor. In order to evaluate degradation of organic matter independent of the biomass separation step, one may look at the removal rate of soluble COD (SCOD). It is demonstrated in figure 5 that the maximum removal rate in a dilute municipal wastewater was found to be around 30 g SCOD/m^2d. This does not, however, give the true picture since biodegradable, soluble organic matter is produced in the process by hydrolysis. An alternative is to evaluate the so-called "obtainable" removal rate, meaning the removal rate of total COD at 100 % biomass separation. Figure 6, that gives the "obtainable" removal rate versus total COD loading rate, demonstrates that high removal efficiencies may be obtained even at extremely high loading rates if good biomass separation can be assured.

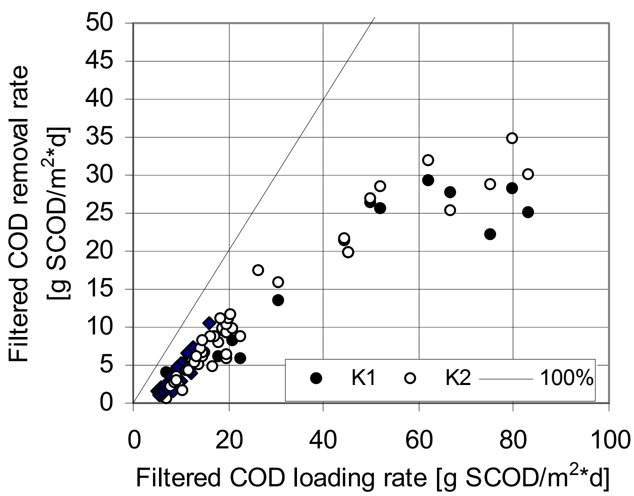


Fig 5. Soluble COD removal rate versus soluble COD loading rate

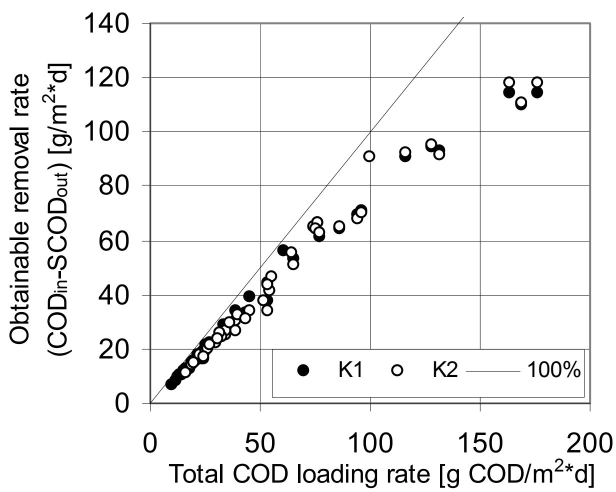


Fig 6 "Obtainable" COD removal rate versus total COD loading rate

It is demonstrated that the design load for COD/BOD-removal (around 20 g COD/m^2d) normally used is very conservative, and that a much higher design load may be accepted when an efficient biomass separation method is employed. In highly loaded plants, clarification of the biomass does, however, represent a problem. The key to solving this problem is biomass flocculation, for instance by adding coagulants (metal salts or cationic polymers) or by using the solids contact process proposed by Norris et al (1982). Research on this is currently being performed.

Figure 4 and 5 also demonstrate that there is not any significant difference between the removal rates of the smaller K1 carrier (effective area 410 mm^2/piece) as compared to the new, larger K2 carrier (810 mm^2/piece) when the removal rate is given in terms of g/m^2d. Of course, the smaller carrier will need a smaller reactor volume at a given loading rate (as g/m^2d) when the carrier filling is the same. The larger carrier will, therefore, only be used when one is afraid of sieve clogging.

BOD/COD removal in combination with P-removal (see figure 4b)
In Scandinavian plants, where phosphate removal is required, chemicals are normally added to the water just after it has left the moving bed reactor and ahead of the flocculation/step (see figure 4b). This ensures good particle separation. Treatment results from two Norwegian plants in1996 and 1997 are given in table 1. In this period the organic loading rate varied in the range of 2-15 g BOD_7/m^2d with typical values around 3-5 g BOD_7/m^2d in the Steinsholt plant while the Eidsfoss plant was low loaded, typically in the range of 1-2 g BOD_7/m^2d. It is demonstrated that high removal efficiencies and low effluent concentrations can be achieved with the moving bed reactor used in this process scheme.

Table 1 Treatment results from two Norwegian plants for organic matter and P-removal

Parameter	Steinsholt treatment plant			Eidsfoss treatment plant		
	In, mg/l	Out, mg/l	% removal	In, mg/l	Out, mg/l	% removal
BOD – ave	398	10	97,4	77[1] (LOC)	6,3[1] (LOC)	91,8[1] (LOC)
max	1720	38	99,7	182	9,8	94,4
min	120	5	93,5	32	4,2	83,6
COD – ave	833	46	94,4	-	-	-
max	2760	130	98,4			
min	190	30	83,2			
Tot P – ave	7,1	0,30	95,8	9,8	0,17	98,2
max	12,0	0,72	98,8	27,5	0,94	99,8
min	4,0	0,12	92.6	4,4	0,03	88,3
SS - ave	-	21	-	-	11	-
max		30			27	
min		8			5	

[1] These values are based on soluble organic carbon (LOC)

High-rate pre-treatment for upgrading of activated sludge plants (see figure 3c)
The very high COD removal rates that can be obtained at high loading rates, demonstrated in figure 6, indicate that the process may be of special interest for high rate treatment plants. For instance it may be used as the first carbonaceous removal step in a two-step process with activated sludge as the second step for upgrading purposes (for instance for nitrification). Quite often this can be achieved in an existing, normally loaded, activated sludge tank.

In such a case, the moving bed reactor may be placed directly in front of the activated sludge plant without any intermediate step, or it may include a separation step after the moving bed reactor (see figure 4c). The benefit of having an intermediate separation step is that the sludge production in the moving bed process will not influence (reduce) the sludge age of the activated sludge process. The benefit of not having an intermediate separation step, in addition to avoiding investment costs for this step, is that the separation properties of the activated sludge may be improved.

An example of this application is the MBBR-solids contact process (no intermediate settling) used at the Western and Moa Point plant in Wellington, New Zealand. Here a pilot plant investigation demonstrated that this process was a very robust and compact alternative for secondary treatment of municipal wastewater (Rusten et al, 1996). BOD-concentration profiles through the pilot plant are shown in figure 7 for test periods with a medium (a) and high (b) organic load on the moving bed reactor stage. One moving bed reactor was used ahead of two activated sludge reactors, all reactors of the same volume. Even though the moving bed reactor constituted only 1/3 of the total reactor volume, figure 7 demonstrates that the major removal of organic matter took place in the moving bed reactor in both test periods.

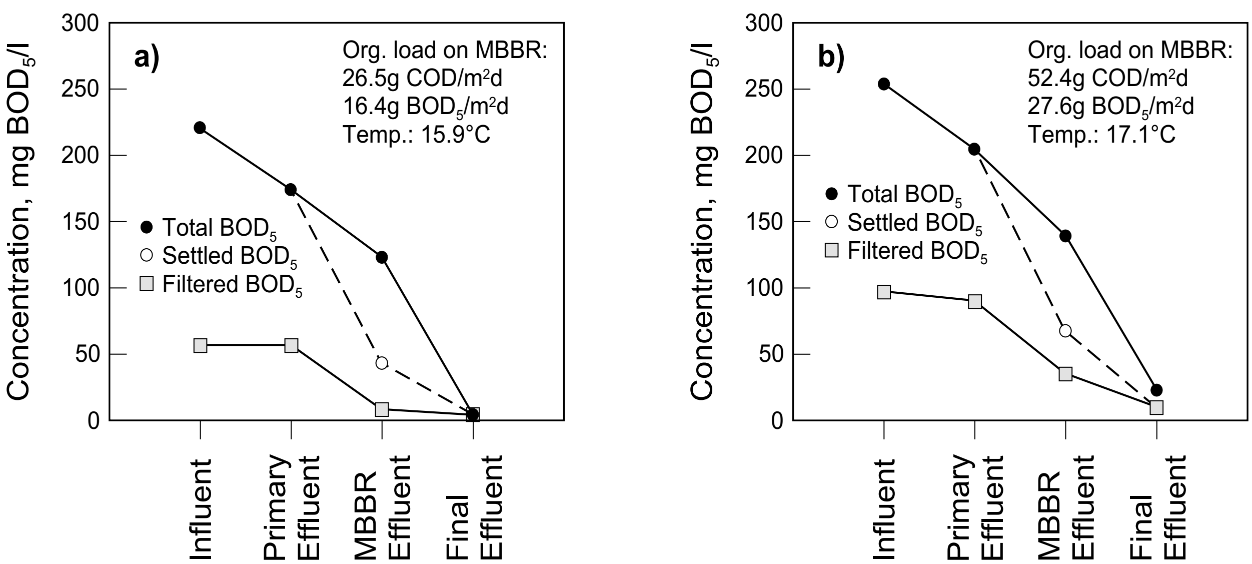


Fig 7 Treatment results from pilot testing of the MBBR solids-contact process with (a) a medium high and a (b) high organic load on the MBBR (Rusten et al, 1996)

The moving bed reactor volume was the same in the two periods and the volumetric organic load was only slightly higher in period b. On a biomass basis, the organic load on the moving bed reactor was also the same in both periods, 2,2 kg BOD_5/kg TS*d. Due to lower filling of carriers in period b the organic area loading was, however, 70 % higher in this period than in period a. As it can be seen in figure 7, the higher area loading caused a pronounced difference in both the moving bed effluent as well as in the final effluent in period b. This illustrates that the organic load per biofilm surface area is the most correct parameter to refer to in the design of the moving bed reactors.

NITRIFICATION

The moving bed biofilm process has very favourably been used for nitrification (Hem et al, 1994, Ødegaard et al, 1994 and Rusten et al, 1995a), with either chemical coagulation or biological carbonaceous removal as pre-treatment. Three factors, the load of organic matter, the ammonium concentration and the oxygen concentration primarily determine the nitrification rate. The influence of these parameters is schematically shown in figure 8.

Figure 8a demonstrates that the organic load is a key factor and should be as low as possible. At loading over about 4 g BOD_7/m^2d, high oxygen concentrations (> 6 mg O_2/l) is required in order for nitrification to take place. As shown in figure 8b, the ammonium concentration is only limiting the nitrification rate at low ammonium concentrations (< 3 mg NH_4-N/l).

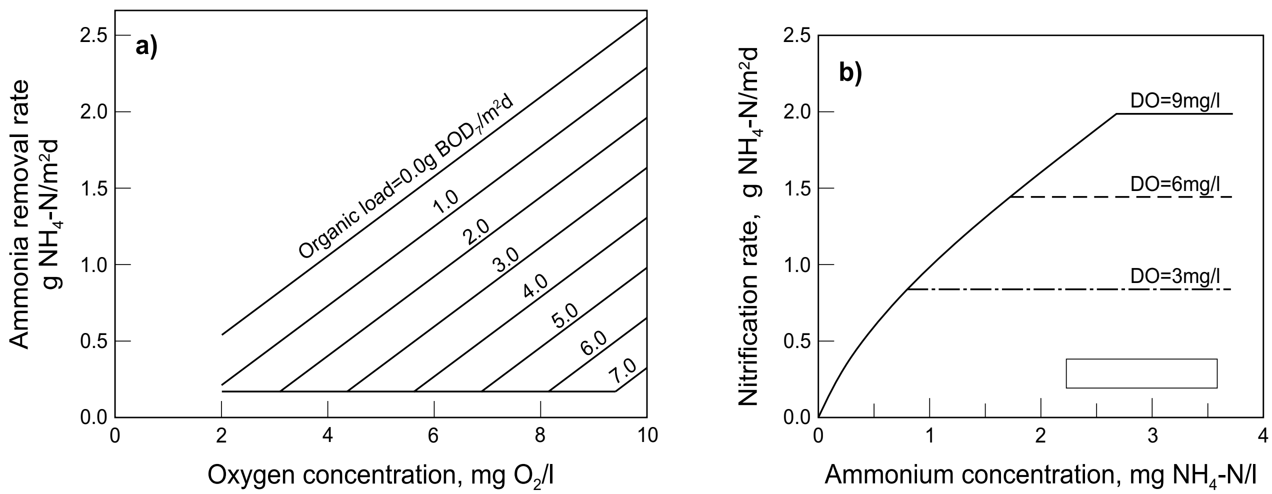


Fig. 8 Influence of BOD_7, oxygen and ammonium on nitrification rate

Far more important is the influence of oxygen concentration that may limit the nitrification rate even at relatively high concentrations. It is experienced that an oxygen level above 2-3 mg O_2/l is needed in order to initiate nitrification. The nitrification rate is found to be close to linearly dependent upon the oxygen concentration, up to more than 10 mg O_2/l (Ødegaard et al, 1994, Æsøy et al, 1998). Above an ammonium concentration of 3-4 mg NH_4-N/l, the nitrification rate is primarily governed by the oxygen concentration and the organic load.

Three different flow schemes are given in figure 4d-f. In figure 4d is shown a process scheme frequently used in Scandinavia, where coagulation is used as pre-treatment, removing phosphate as well as particulate and colloidal organic matter. In this case the load of particles (biomass) on the nitrifying reactors will be less than in the process of figure 4e. This results in higher nitrification rates. In figure 4e nitrification takes place directly after organic matter removal without any intermediate separation step. In contrast to an activated sludge system, the heterotrophs will dominate in the start of the process (first reactor) and the nitrifiers in the end of the process (last reactor). This makes it possible to optimise each of the processes independent of the other.

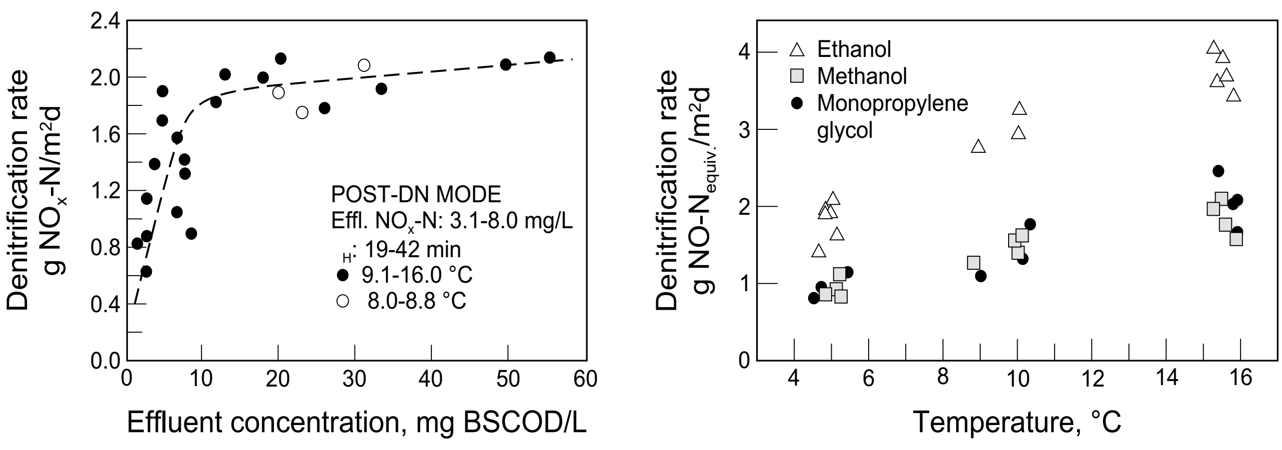
In figure 4f is shown a system where the nitrification reactors are placed after a conventional activated sludge plant ensuring that no biodegradable organic matter is limiting the nitrification rate of the moving bed reactor. The sludge production in the nitrifying step will be so low, that in many instances, biomass separation will not be needed. In plants with a stringent effluent standard, direct filtration (as shown in figure 4f) may be an option.

NITROGEN REMOVAL

Nitrogen removal in moving bed biofilm plants may be achieved by several process combinations, for instance pre-denitrification (figure 4g), post-denitrification (figure 4h and 4i) or a combination of the two – the so-called combined denitrification process (figure 4j).

The denitrification rate may be limited by the nitrate concentration, the biodegradable organic matter concentration or by the oxygen concentration (or rather the presence of oxygen). At NO_3-N concentrations above about 3 mg NO_3-N/l, the denitrification removal rate will be completely governed by the type and availability of easily biodegradable carbon source. If oxygen is supplied to the reactor with the inlet water or recirculated water, biodegradable organic matter will be consumed for oxygen respiration and thus reduce the available amount for denitrification.

The limitation of the pre-denitrification process (figure 4g) stems from the fact that oxygen-rich water from the nitrification step will have to be returned to the pre-denitrification step. The raw water carbon source is very often not sufficient, and the denitrification rate in pre-denitrification systems will normally be limited by the carbon source availability and consequently be rather low. In post-denitrification systems, one has to add carbon source and since this will be easily biodegradable, a very high denitrification rate may be expected. Examples are given in figure 9.



a. DN-rate versus biodegradable, soluble COD concentration (Rusten et al, 1995a)

b. DN-rates versus temperature with different carbon sources (Rusten et al, 1996b)

Fig. 9 Examples of denitrification rates determined in pilot plant reactors

The post-denitrification mode has several advantages over the pre-denitrification mode. It may lead to considerably lower total bioreactor volumes (40-50 %) and it gives much better process control. The major drawback with the post-denitrification process, is the need for carbon source addition.

In order to minimise the use of carbon source, the flow scheme of figure 4j, combined denitrification - has been preferred in several Norwegian plants. The combination process offers greater flexibility with respect to operation of the plant. In periods when the organic load is high or the water is very cold, one may reduce the organic load by using pre-coagulation. The organic matter in the coagulated wastewater will partly consist of low molecular weight, easily biodegradable organic matter (20-40 mg BSCOD/l), that has the capacity to denitrify a certain amount of nitrate (4-8 mg/l). This is brought to the pre-denitrification step by a moderate recirculation flow (0,25-0,5 times Q) thus minimising oxygen recirculation. The rest of the nitrate is removed in the post-DN step where the measured effluent nitrate concentration controls the carbon source addition.

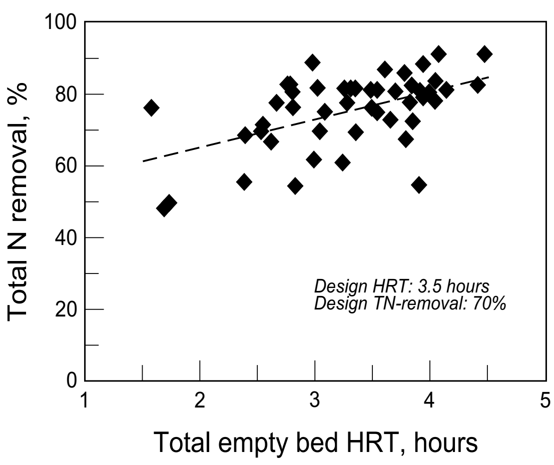
In table 2 are shown results from the Lillehammer treatment plant in Norway. At maximum design load this plant is supposed to operate with pre-coagulation. At the present loading situation, pre-coagulation is not needed, however. As a test procedure, only one of the two trains was operated the summer of 1997 resulting in loads close to or above the design load.

Table 2 Tot N removal at Lillehammer treatment plant at design load (July-Oct 97)
(Plant operated in post-denitrification mode without pre-coagulation)

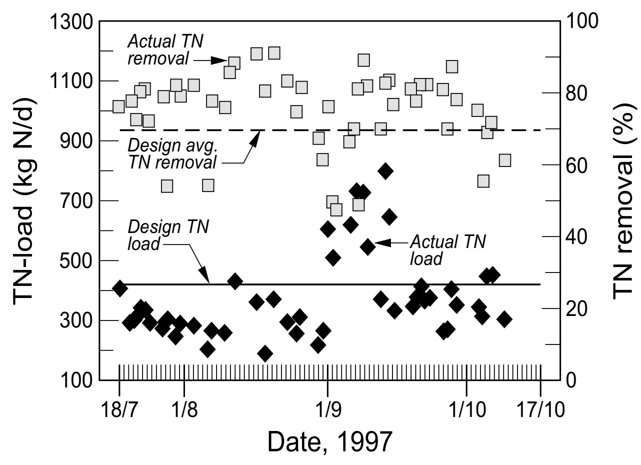
	Bioreactor residence time (hrs)	Influent Tot N conc. mg N/l	Effluent Tot N conc. mg N/l	Removal %	Ethanol consumpt. kg /kg $N_{rem.}$	Temp-erature ^{o}C
Average	3,3	27	6,0	76	1,48 (3,1)[1]	13,7
Minimum	1,6	16	2,9	48	0,55 (1,2)[1]	11,6
Maximun	4,5	48	12,7	91	2,58 (5,4)[1]	15,7

[1] kg COD/kg $N_{removed}$

In figure 10a is the total N removal efficiency for each day in the period plotted versus total bioreactor residence time. The day to day removal of total N is shown in figure 10b, together with actual flow, actual total N load and the corresponding design values.



a. Treatment efficiency versus total bioreactor time (based on empty reactor)



b. Day to day removal efficiency of tot N residence at actual load compared to design load

Fig 8 Treatment results from the Lillehammer treatment plant at and above design load, when operated in the post-denitrification mode without pre-coagulation

In table 3 are shown treatment results from the same plant, now operated as in combined denitrification mode without pre-coagulation at only 60 % of the design load but at very low temperatures. The good results from the Lillehammer plant demonstrate the great flexibility of the combination process, making this a very favourable alternative in wastewater situations frequently encountered in Scandinavia, with great variations in temperature and wastewater characteristics (e.g. availability of easily biodegradable carbon source).

Table 3 Treatment results from the Lillehammer plant when operated in the combination-DN mode at very low temperatures.

	Temp-erature, ^{o}C	Average influent inorg. N conc. mg N/l	Average effluent inorg. N conc. mg N/l	Removal inorg. N %	Fraction of denitrification in pre-DN, %
Average	6,3	17,2	3,1	92,0	16
Minimum	6,0	16,1	2,2	74,5	15
Maximum	6,5	17,7	4,1	87,6	17

DESIGN VALUES

Design of the moving bed biofilm reactor must, of course, be based on the actual wastewater characteristics and local circumstances in each case. Even if the design values given in table 4 are typical for the different processes, they are given for illustration purposes only.

In a plant, the reactors are normally placed after each other in series, and the design may be carried out for each of the reactors in series based on the load that is entering this reactor from the previous one in the series.

Design according to these values will result in very compact treatment plants.

Table 4. Typical design values for KMT reactors at 15 ^{o}C

Purpose	Treatment ambition % removal	Design loading rate, g/m^2d	Design loading rate kg/m^3d at 67 % fill
BOD-removal			
High-rate	75-80 (BOD_7)	25 (BOD_7)	8 (BOD_7)
Normal rate	85-90 (BOD_7)	15 (BOD_7)	5 (BOD_7)
Low rate	90-95 (BOD_7)	7,5 (BOD_7)	2,5 (BOD_7)
Nitrification (O_2>5 mg/l)			
BOD-removal stage[1]	90-95 (BOD_7)	6,0 (BOD_7)	2,0 (BOD_7)
NH_4-N > 3 mg/l	90 (NH_4-N)	1,00 (NH_4-N)	0,35 (NH_4-N)
NH_4-N < 3 mg/l	90 (NH_4-N)	0,45 (NH_4-N)	0,15 (NH_4-N)
Denitrification			
Pre-DN (C/N>4)[2]	70 (NO_3-N)	0,90 (NO_3-N)	0,30 (NO_3-N)
Post-DN (C/N>3)[2]	90 (NO_3-N)	2,00 (NO_3-N)	0,70 (NO_3-N)

[1] O_2> 3mg /l [2] g BOD_7/g NO_3-$N_{equiv.}$

CONCLUSIONS

The moving bed biofilm reactor has established itself as a well-proven, robust and compact reactor for wastewater treatment. The efficiency of the reactor has been demonstrated in many process combinations, both for BOD-removal and nutrient removal. It has been used for small as well as large plants.

The primary advantage of the process as compared to activated sludge reactors, is its compactness and no need for sludge recirculation. The advantage over other biofilm processes, is its flexibility. One can use almost any reactor shape and one can choose different operating loads in a given reactor volume, simply by choice of carrier filling.

Even though it has been focused on municipal wastewater applications in this paper, the reactor has been used also for industrial wastewater, particularly in the food industry and the pulp and paper industry. Tests are also being performed on anaerobic wastewater treatment as well as drinking water treatment.

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