THE INFLUENCE OF CARRIER SIZE AND SHAPE IN THE MOVING BED BIOFILM PROCESS

Hallvard Ødegaard*, Birgitte Gisvold** and Jonathan Strickland***

* *Faculty of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), N-7491 Trondheim, Norway*

** *SINTEF Civil and Environmental Engineering at NTNU, N-7465 Trondheim, Norway*

*** *Anglian Water Services, Huntingdon, Cambs. PE18 6XQ,, UK*

ABSTRACT

The moving bed biofilm process is based on plastic carriers on which biomass attaches and grows. The original Kaldnes carrier was made of high-density polyethylene (density 0,95 gcm^{-1}) that could be used in filling fractions (volume of carriers in empty reactor) up to 70 % that gives a specific area of 350 m^2m^{-3}. Lately there has been an interest in the use of larger carrier elements, especially when using the process for upgrading of activated sludge plants. This paper analyses the influence of the carrier size and shape on performance, especially related to highly loaded plants working on municipal wastewater. The results demonstrate that moving bed biofilm reactors should be designed based on surface area loading rate (g COD/m^2d) and that shape and size of the carrier do not seem to be significant as long as the effective surface area is the same. The results indicate that very high organic loads can be used in order to remove soluble COD but that the settleability of the sludge is negatively influenced at high loading rates.

KEYWORDS

Moving bed biofilm reactor, organic loading, performance, kinetics

INTRODUCTION

The moving bed biofilm process (Ødegaard et al, 1992, Ødegaard et al, 1998) is becoming increasingly popular and is now being used in more than 100 plants around the world for various treatment purposes (BOD/COD-removal, nitrification, denitrification) in both municipal and industrial wastewater. The basic principle of the process is that the biomass grows on plastic carriers that move in the reactor because of the agitation set up by aeration (in aerobic reactors) or mechanical mixing (in anaerobic and anoxic reactors). The carriers are made of polyethylene with a density close to 1 g/cm^3, which allows them to move easily in the reactor even up to filling fractions (volume occupied by carriers in empty reactor) of 70 %. Because the reactor is completely mixed, the whole reactor volume is active - in contrast to most of the other modern biofilm reactors on the market.

The original Kaldnes carrier (K1) is shaped like a cylinder (length 7 mm and diameter 10 mm) with a cross inside the cylinder and fins on the outside (see Figure 2). A sieve is needed to keep the carriers within the reactor. This is normally a vertically mounted, rectangular mesh sieve, but it is sometimes shaped as a cylindrical bar sieve vertically or horizontally mounted, in either case using 5 mm slots. One advantage of the process is that it may be favourably used to upgrade activated sludge plants. Many activated sludge plants are, however, designed without a primary settling tank and with 6 mm inlet screens, and for this reason there has been a demand for larger carriers in order to avoid clogging of the sieves. An objective for process development, therefore, was to use a media retention sieve of 10 mm opening, giving greater operator confidence when using 6 mm inlet screens. It was decided, therefore, to carry out an experimental investigation of the influence on performance of size and shape of carriers that may be used in the moving bed biofilm process.

DESIGN OF BIOFILM PROCESSES

The substrate removal rate in a biofilm process can be expected to be is first order dependent on the bulk concentration at very low concentrations. At higher bulk concentrations the reaction order is reduced, as substrate concentration increases, via ½ order (when transport of substrate through the biofilm is limiting the rate) to zero order at very high bulk concentrations (where the enzyme kinetics for substrate consumption is the limiting factor). When considering definite substrates such as acetic acid, ammonia or nitrate, the rate/concentration curve can easily be established and the kinetics studied. This is much more difficult when considering a mixed substrate, such as the organic matter of municipal wastewater. The various specific compounds that make up the COD will have different kinetic characteristics, thus making the rate characteristics of COD removal dependent on the local composition of the wastewater, that may vary considerably over time and from place to place.

It is accepted, however, that the performance of a biofilm reactor is primarily dependent upon the biofilm growth surface area in the reactor and not on the reactor volume. Many biofilm reactors (such as RBC's) are, therefore, designed based on specific area removal rate (kg substrate/$m^2_{biofilmarea}\cdot$d). Design of biological filters is, however, normally related to volumetric removal rate (kg substrate/$m^3_{reactorvolume}\cdot$d). The reason is probably the difficulty in determining the effective surface area of biofilm growth on carriers in trickling filters or granular media filters. From the start also the moving bed biofilm process was designed according to the volumetric removal rate. In order to take effective biofilm area into account, one had to relate design to the specific area of the carrier as well as the filling fraction of the carrier in the reactor.

It has become common to present kinetic results from pilot studies in a removal rate versus loading rate plot. The results are normally well fitted to a hyperbolic equation: $r = r_{max} \cdot L/(K+L)$, where r and r_{max} are the actual and the maximum substrate removal rate respectively and L is the substrate loading rate. K is a constant. When presenting results from three carriers of different sizes, e.g. specific surfaces, in terms of volumetric rates, the results would come out as in Figure 1a. It is demonstrated that in the lower substrate loading rate range (shaded area), carriers of different size and specific surface seem to give almost the same removal rate at a given volumetric substrate loading rate. This is, however, caused by the fact that the carrier with the lower specific surface area has a higher area loading rate, resulting in a corresponding higher removal rate than carriers with a higher specific surface. The three carriers are, in other words, not compared at the same loading rate from a process point of view in Figure 1a. If the effective surface area is the decisive parameter in the relation between removal rate and loading rate, the results from all carriers will fall along the same curve, when presented in terms of surface area rates, as shown in Figure 1b.

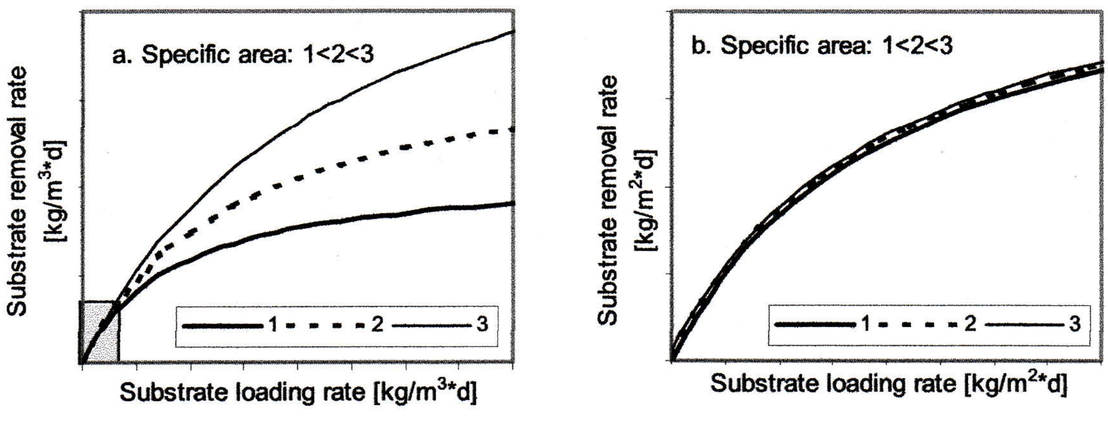


Fig. 1 Presentation of removal rate versus loading rate for three carriers of different specific surface areas

A complicating factor in the analysis is the hydrolysis of organic matter within the reactor. The extent of hydrolysis is not only dependent upon the biomass, but the time that the biomass stays in the reactor as well. The sloughing of biomass is not in steady state and therefore the amount of suspended biomass due to sloughing is varying. And then there is the matter of hydrolysis of the particular organic matter that enters the reactor with the raw water. How much of the particulate COD is turned into soluble COD (SCOD) by hydrolysis? How would that influence on COD removal? This could be taken care of by analysing on total COD. However, when analysing on total COD the separation of the biomass has to be taken into account.

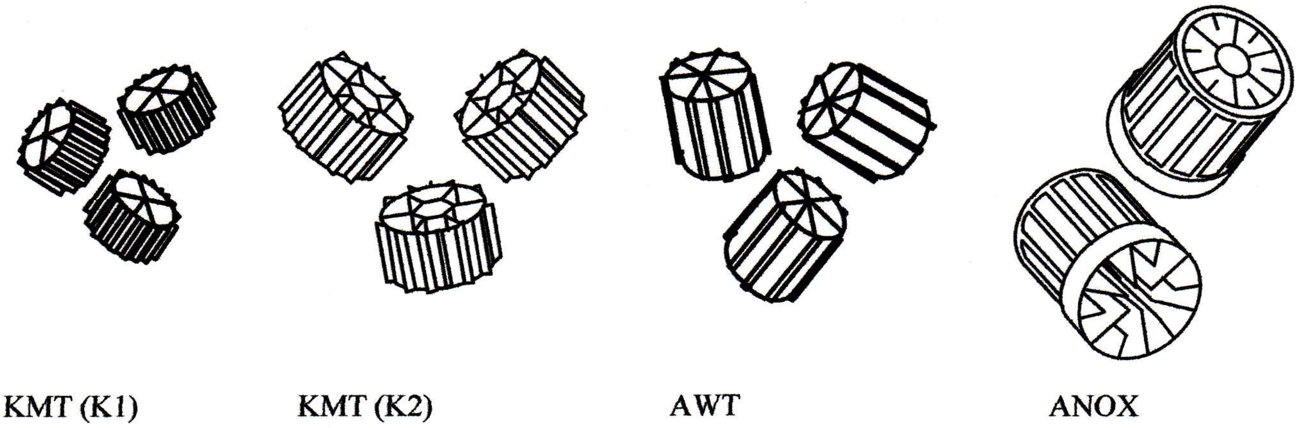
EXPERIMENTAL INVESTIGATION

It was decided to carry out a comparison test at various COD loads using various carriers of different size and shape, but the same density, and analyse the results both on the basis of volumetric removal rate as well as on area removal rate basis. The experiments were carried out in identical pilot plants, consisting of one moving bed reactor and a corresponding settling tank, operated in parallel on the same water.

In the first part of the experiments, three parallel lines each consisting of one moving bed reactor and one settling tank, were used. The volumes of the bioreactors were 20 l (line 1 and 2) or 30 l (line 3). The moving bed reactors contained three different types of carriers (see Figure 2) and were operated at relatively high organic loads (10-120 g COD/m^2d and 5-45 g SCOD/m^2d). The surface of the settling tanks was 0,068 m^2 (line 1 and 2) or 0,102 m^2 (line 3), resulting in an overflow rate of 0,26 m/h on average. This first part of the experiments was carried out in two different periods. In the first period, all three reactors with the same filling fraction (60 %) were given the same volumetric load, while in the second period the filling fraction was varied to give the same effective area load at constant flow. The results from this first part of the experiments resulted in the decision to make a larger Kaldnes carrier (K2).

The second part of the experiments was devoted to a comparison between the two Kaldnes carriers (K1 and K2) carried out in line 1 and 2 of the same pilot plant. The two lines were operated in three periods at close to constant flow in each period (e.g. the same residence time) and hence the same volumetric loading rate. The flow of the three periods corresponded to average residence times of 375, 52 and 27 min and overflow rates of 0,05, 0,35 and 0,65 m/h respectively. The filling fraction was 70 % in both reactors.

The shape of the four carriers tested is shown in Figure 2 and other carrier characteristics are given in Table 1. The KMT carrier K1 is the original Kaldnes carrier that is mostly used. The larger AWT carrier was made for this experiment by Anglian Water. The ANOX carrier has the shape, but not the density, of another commercial carrier made by ANOX. Here, all carriers were made of high-density polyethylene (density 0,95 g/cm^3) in order to avoid influence of buoyancy differences. The surface areas given in Table 1 are estimations to the best of our ability. The total surface area consists of both inner and outer surfaces, while the effective surface area is that where biofilm seems to attach. The effective surface area of the KMT K1 and the AWT carriers were calculated as the whole inner area plus the area of the outer fins. The area between the fins was not included since visual inspection did not show any sign of growth here. For the ANOX carrier, the effective area is calculated as the inner area since there are no fins with outer area.



KMT (K1) KMT (K2) AWT ANOX

Fig. 2 The four biofilm carriers used

Table 1 Characteristic data for the four different carriers used.

Specific surface area	KMT carrier K1	KMT carrier K2	AWT carrier	ANOX carrier
Estimated surface area [mm^2/piece]	total : 670 effective : 490	total : 3465 effective : 1910	total : 2200 effective : 1500	total : 10000 effective : 7700
Bulk carriers [number/litre]	1030	159	203	24
Specific surface area [m^2/m^3]	total : 690 effective : 500	total : 550 effective : 315	total : 450 effective : 310	total : 240 effective : 190

Wastewater characteristics

In Table 2 the wastewater characteristics for the various experimental periods are given. In period 1 (first part of the experiments) as well as in period 3 (second part of the experiments), the wastewater composition was as it is normally at the pilot station of the university. This station is draining an urban area with parking lots etc, resulting in a quite dilute wastewater. In the second period (first part of the experiments) the organic content of the wastewater was raised by the addition of dried milk in order to be able to come up to the high organic loads that were desired.

Table 2 Average, maximum and minimum influent values for the pilot plant

	1st. part of experiments						2 nd. part of experiments		
	Period 1			Period 2			Period 3		
	Average ± stand.dev.	Max. value	Min. value	Average ± stand.dev.	Max. value	Min. value	Average ± stand.dev.	Max. value	Min. value
SS	136 ± 98	505	53	152 ±55	232	58	88 ± 18	136	53
COD	323 ±166	893	139	498 ±235	915	125	219 ± 66	435	119
SCOD	123 ± 39	236	69	219 ±128	431	36	100 ± 38	211	42
pH	7.3 ±0.2	8.0	7.0	6.7 ± 0.3	7.1	6.5	7,5 ± 0,1	7,8	7,4

In the first part of the experiments (period 1 and 2), the raw water temperature was in the range of 10-15°C (control). The oxygen concentration was on average 3,5 - 4,5 mg O_2/l in period 1 and 6,2 - 6,4 mg O_2/l in period 2 in all lines. In the second part of the experiments, the temperature was varying relatively little around an average of 11°C (11 ± 1,4) in both lines (with K1 and K2 respectively) while the oxygen concentration varied a bit more. The O_2- concentration was, however, about the same in the two lines, on average 5,6 (± 3,0) mg O_2/l in the line with K1 and 5,4 (± 2,8) mg O_2/l in the line with K2. In this range the O_2-concentration is not expected to have any influence on the rate of COD-removal.

RESULTS

In figure 3 the removal rate versus loading rate with respect to soluble COD (SCOD - COD in samples filtered though a 1,2 µm GF/C-filter) in the first part of the experiments (period 1) is shown, presented both in terms of volumetric rates (Figure 3a) and effective surface area rates (Figure 3b).

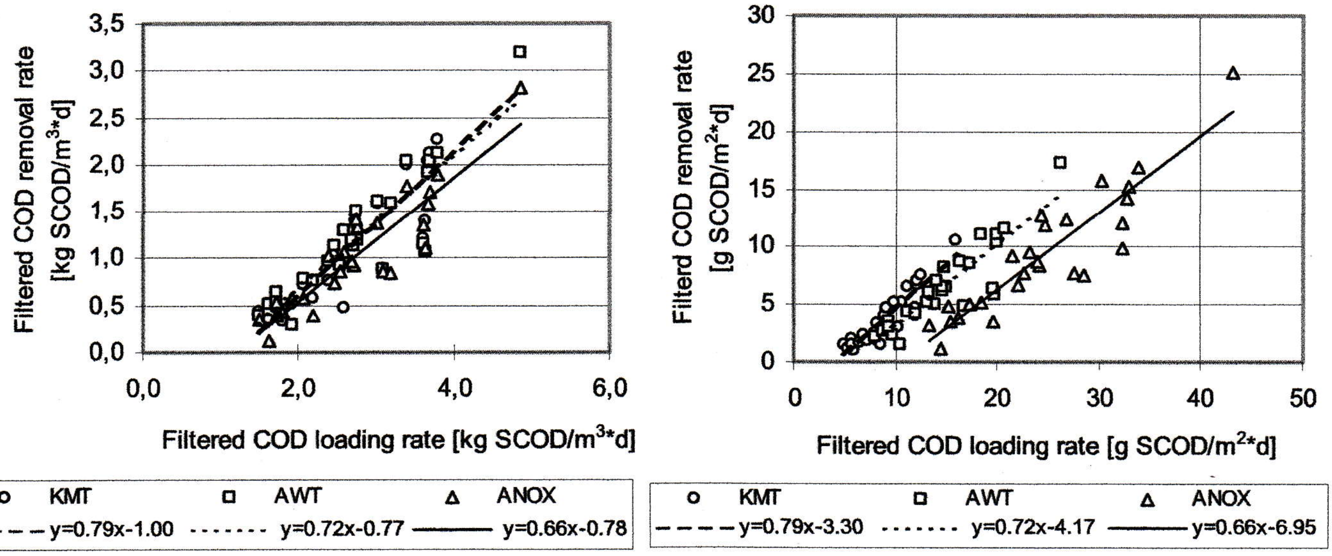


Fig. 3 Removal rates versus loading rates for filtered COD (SCOD) in period 1

From Figure 3a it may look as if the three reactors are performing close to equally well and one could draw the erroneous conclusion that the size and shape of the carrier did not have any influence. From Figure 3b, however, it becomes clear that the reason for the close to equal volumetric removal rates at a given volumetric loading, is that the larger carriers have higher area loads with corresponding higher removal rates. It can be seen that the slope of the regression lines decrease as the carrier size increase. This is in accordance with the fact that a removal rate versus loading rate curve will slowly level off as loading rate increases. In the experiments in period 1 the loading that gave the maximum removal rate was never reached. According to Figure 1, one would expect that in Figure 3b the data points, should all fall along the same line. The results indicate, in fact, that the smaller KMT carrier performed slightly better than the AWT carrier and significantly better than the ANOX carrier. It is not clear why this was so, but it may be due to incorrect estimations of effective area.

In order to evaluate the influence of carrier area further, experimental period 2 was undertaken, in which the number of carriers were reduced in the KMT- and the AWT-reactor, so that all the reactors had the same effective surface area (110 m^2/m^3). The resulting filling fractions were 22 % in the KMT-reactor, 36 % in the AWT-reactor and 60 % in the ANOX-reactor. The organic load was increased (by the addition of dried milk) in an attempt to reach the maximum removal rate. In Figure 4 the removal rate with respect to SCOD versus loading rate in g SCOD/m^2d in period 2 is shown. It is demonstrated that there was little difference in performance between the three different reactors. The maximum rate of 25-30 g SCOD/m^2d seemed to be reached at a loading around 60 g SCOD/m^2d. The data point line up to this loading is close to linear, indicating that the availability of biodegradable organic matter was limiting the degradation at loads lower than about 50 g SCOD/m^2d. The difference between this line and the 100 % removal line represents, therefore, the soluble COD that could not be biodegraded in this water within the actual residence time.

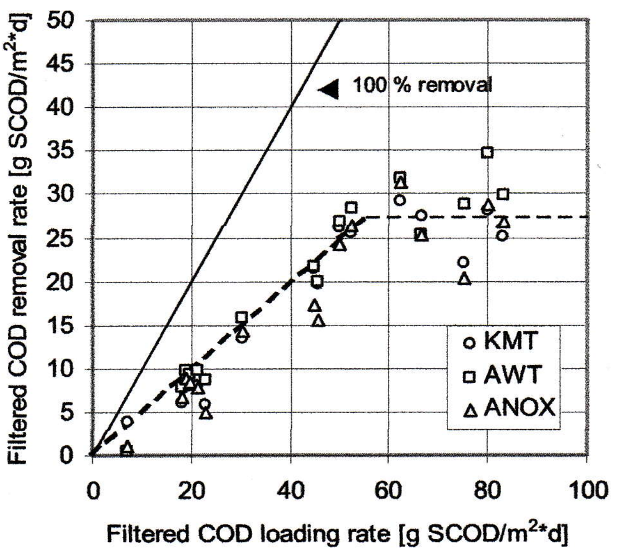


Fig. 4 SCOD area removal rate versus area loading rate in period 2. All reactors same carrier area

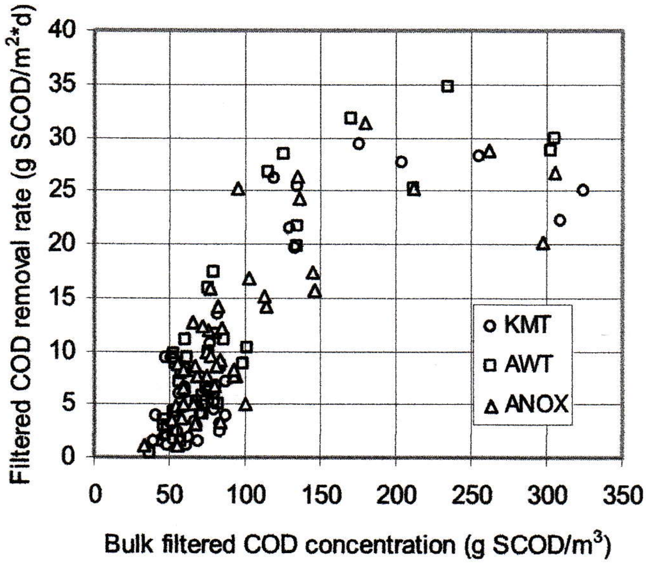


Fig. 5 SCOD area removal rate versus bulk SCOD concentration. All data from period 1 and 2

In Figure 5 the SCOD area removal rate has been plotted against bulk water SCOD concentration. Even though there is quite some scatter that is to be expected in such a presentation, it can be shown that the reaction order is close to 1/2 order up to about 200 g SCOD/m^3 and zero order in the high concentration range (> 200 g SCOD/m^3). This is in good agreement with the kinetic theory of biofilms. It is demonstrated that about 40 mg SCOD is not biodegraded at the actual residence time (65 min).

In Figure 6a all the SCOD removal rate data from both periods of the first part of the experiments are plotted versus SCOD loading rate. In this larger loading range than Figure 3 represented, it can be seen that there are no significant differences between the carriers. This can be taken as an evidence of the fact that the key parameter for designing moving bed processes is the effective surface area and that the shape and size of the carriers are of less importance as long as the effective surface area of the reactor is the same.

In part two of the experiments (period 3), the two Kaldnes carriers K1 and K2 were compared. The two pilot plants were operated at the same flow in three levels corresponding to average bioreactor residence times of on average 375, 52 and 27 min respectively. The filling fractions of the bioreactors were also the same (70 %) corresponding to effective specific surfaces of 350 m^2/m^3 (K1) and 220 m^2/m^3 (K2). In figure

6b the SCOD removal rate versus loading rate is given for all the data of this period. Once again it is demonstrated that the results more or less fall along the same line which supports the finding above that there is not much difference between the two carriers when compared on surface area basis.

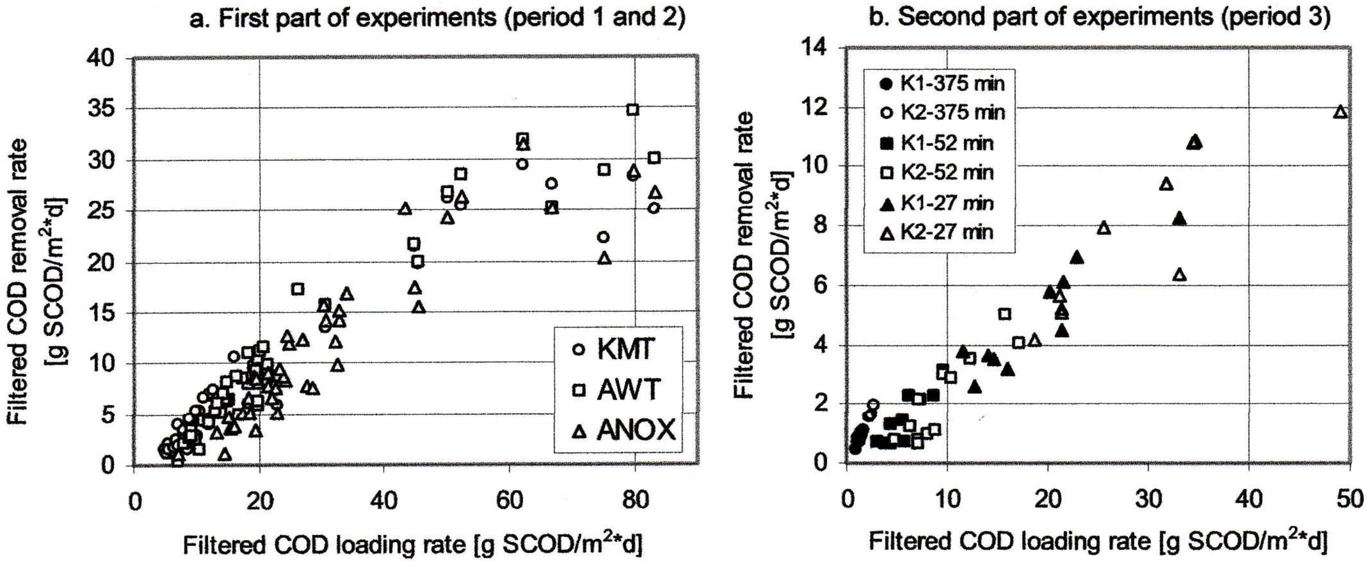


Fig. 6 SCOD removal rates versus loading rates

We can also see that there is not much difference between the results at 27 min residence time as compared to those at 52 min. It is interesting to note from Figure 6b, however, that at a very long residence time (375 min), the slope of the removal/loading rate relationship is significantly higher than that at the lower residence times (52 and 27 min). A straight curve through the data for the lower residence times seems to cross the x-axis at a value that corresponds to a concentration of 35-40 mg SCOD/l, while a similar curve for the long residence time seem to cross the x-axis much closer to the zero value. Our interpretation of this is that slowly biodegradable organic matter is hydrolysed in the long residence time situation much more extensively than in the low residence time situation. This means that residence time does have an influence on the removal results – at long residence times.

Above we have concentrated on the removal of soluble (filtered) COD. It is not easy to analyse the total COD removal rates in the bioreactor alone, since both the soluble and the particulate organic matter changes its characteristics through the reactor by hydrolysis, assimilation etc. In order to be able to take the particulate matter into account, we have analysed what one may call the "obtainable" COD removal rate defined as: $(COD_{influent}-SCOD_{effluent})*Q/A$ where Q is the flow and A is the effective surface area of the carrier. This term illustrates the removal rate of organic matter if all particles larger than 1,2 μm were removed in a downstream separation step, see Figure 7. In both data sets, from first as well as from second part of the experiments, the data from the different carriers again fall along the same line. It is demonstrated that the curve levels off very slowly and that very high loading rates (> 100 g COD/m^{2}d) can be used without losing much on the removal rate of filtered COD. The data from the first part of the experiment (Figure 7a) shows that 85-90 % removal of COD could have been obtained all the way up to a loading rate of 100 g COD/m^{2}d, if the biomass downstream the bioreactor had been completely removed. The reason for the somewhat poorer removal in the second part of the experiment must stem from the fact that the water was more dilute then with a greater portion of the total COD that was not biodegradable.

In a total removal analysis, one has to take into account the separability of the biomass. In these experiments very small pilot plants were used, and it is very difficult to analyse settling characteristics in such small settling tanks. Nevertheless, we shall analyse the settling data from the second part of the experiments where the Kaldnes carriers (K1 and K2) were compared. Since the pilot plants were operated at a given hydraulic load, corresponding to bioreactor residence times of 375 min, 52 min and 27 min, this also resulted in a given overflow rate in the settling tanks of ca 0,05, 0,35 and 0,65 m/h respectively.

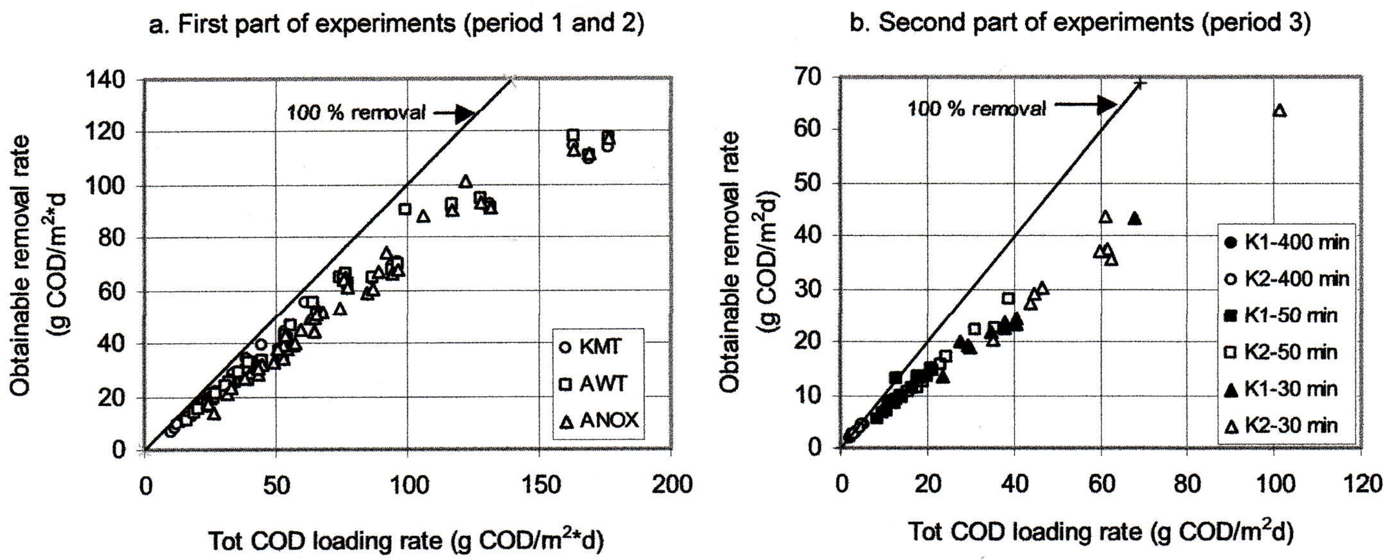


Figure 7 "Obtainable removal rate versus total COD loading rate

Figure 8 show the SS-removal efficiency versus the total COD as well as SCOD area loading at different overflow rate. The different overflow rates correspond to the three levels of flow and consequently to different levels of organic loading on the bioreactor. This makes the analysis a little complicated.

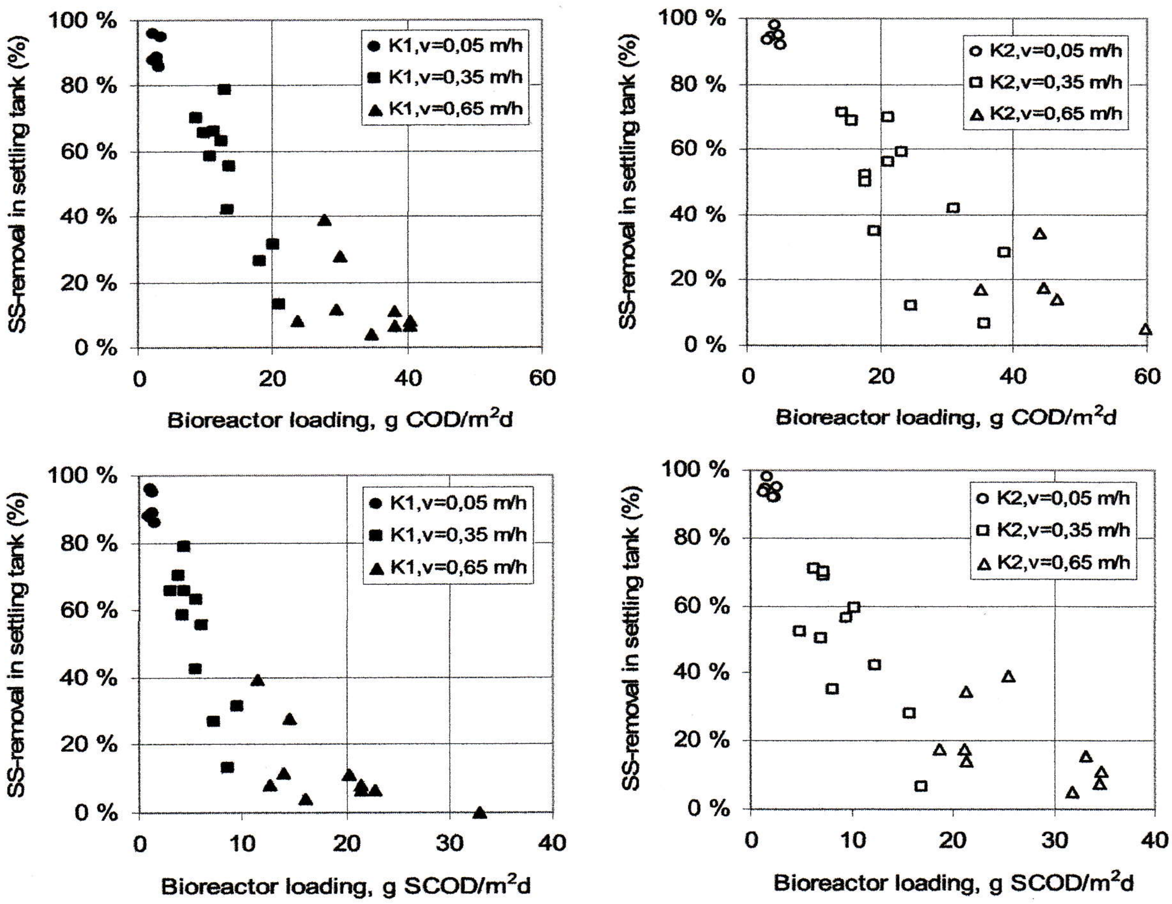


Figure 8. Influence of organic loading rate in bioreactor on settleability

First of all it is obvious that both the overflow rate and the organic loading on the bioreactor has a pronounced effect on settleability. At low organic loading and low overflow rate, the separation of SS is very good but it is poorer at the higher overflow rates that also give higher organic bioreactor loads. For each of the overflow rates, however, there is a decrease in settleability when the organic load is increasing. One cannot judge correctly the influence of organic bioreactor load on settleability by analysing the total COD diagrams alone, since a considerable part of the removed SS is coming in with the raw water. When taking into account that the same influence is seen in the SCOD diagrams, it can be concluded without doubt that increasing the organic load on a moving bed reactor decreases the settleability. By analysing the results from K1 versus those of K2, it seems that the settleability of the biomass from K2 is somewhat better than with K1. The reason for this is not known.

DISCUSSION

From the results obtained in these experiments, it seems clear that the key factor in the design of a moving bed process for organic matter removal is the effective surface area on which the biomass may grow. The size and shape of carriers may have an influence on this effective area, but once this area is established for a given carrier there does not seem to be any difference among carriers. The design of the process should therefore be based on organic surface area removal rate.

At a given organic effective surface area load, the smaller carrier would need much less bioreactor volume than larger carriers. At low loading rates or when treating strong waste, corresponding to long residence times (> 2 hours), an effect of hydrolysis of slowly biodegradable organic matter can be expected and in this situation an influence of the residence time is to be expected. The longer the residence time, the better the efficiency. But this increase in efficiency is, of course, marginal. The benefit of the moving bed process for organic matter removal is primarily connected to high-rate systems and low residence times, because of the cost of the carrier media itself. At high organic loads and low residence times (< 60 min), one cannot expect hydrolysis to take place to a great extent. The particles and other slowly biodegradable organic matter in the wastewater entering the reactor, pass through without being altered much while the soluble and more easily biodegradable matter is degraded very quickly. In fact these experiments demonstrate that much higher design loads than used today, could be applied for this purpose, up to 30 g SCOD/$m^2 \cdot$d, that in many wastewaters would correspond a total COD load of about 100 g tot COD/$m^2 \cdot$d.

The problem, however, with such high loads, is the separation of the biomass, since these experiments demonstrate that the settleability deteriorates with increasing bioreactor load. The natural consequence of this is that settling should be enhanced by coagulation (by adding metal salts or organic polymers) or that separation techniques other than plain settling should be applied.

CONCLUSIONS

From these experiments the following conclusions may be drawn:

1. The design of moving bed biofilm reactors for the removal of organic matter in municipal wastewater should be based on the organic surface area loading rate (g COD/$m^2 \cdot$d). This is also the case when comparing moving bed reactors with different type of carriers.
2. As long as the comparison is made on this basis, the results obtained with carriers of different size and shape, did not vary significantly.
3. Residence time of the bioreactor has only an influence at long residence times (> 2-3 hours) when hydrolysis of particulate and slowly biodegradable organic matter will have an impact. In high rate systems (short residence times), hydrolysis plays a minor role and the reactor should be designed for the removal of easily biodegradable, soluble organic matter. Design values as high as 30 mg SCOD/$m^2 \cdot$d may be used.
4. The settleability of the biomass leaving the bioreactor decreases with increasing organic loading. High rate systems should therefore use enhanced settling by coagulation or alternative separation techniques.

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