Behaviour of Anaerobic Baffled Reactor Treating Nonacidified Wastewater*

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Nonacidified wastewater has been treated in an anaerobic baffled reactor (ABR). The performance of ABR was compared with an upflow anaerobic sludge bed (UASB) reactor. In this work, two types of wastewater were used. The first synthetic wastewater contained starch, peptone, macro- and micronutrients. Hydroxyethylcellulose (HEC) was the major component of the second wastewater. Investigation of the function of the reactors consisted in a gradual increase of the organic loading and observing response of the reactors. Using the substrate which contained starch and peptone, organic loading of 12—15 kg m^{-3} d^{-1} was reached. The efficiencies of Chemical Oxygen Demand (COD) removal with starch wastewater were comparable for ABR and UASB reactor, they were about 80—90 %. A faster biomass granulation was observed in ABR than in UASB reactor. Methanogenesis was the limiting step in anaerobic degradation of the starch substrate. It was assumed that at high organic loading by using nonacidified wastewater, hydrolysis and acidogenesis would be faster in ABR than in UASB reactor. Therefore, HEC was used as a substrate, because this substrate is hydrolyzed slowly. The efficiency of COD removal was about 40 % in the case of HEC.

The anaerobic baffled reactor (ABR), initially developed by *McCarty* and *Bachmann*, consists of a series of baffled compartments where the wastewater flows upward through a bed of anaerobic sludge [1]. The ABR has many potential advantages, *i.e.* stability under hydraulic shock loading, low sludge generation, low capital and operating costs coupled with mechanical simplicity. There is only one full-scale application of ABR in a small town Tenjo in Columbia. This application consists of two ABR's (volume 2 × 197 m^3) with 8 compartments each treating domestic wastewater. The reactors performed well with approximately 70 % Chemical Oxygen Demand (COD) reduction and 80 % removal of suspended solids over a two-month period [2]. Although a detailed economic study was not presented, construction costs of ABR were 20 % less than those of an upflow anaerobic sludge bed (UASB) reactor in Columbia running at ambient temperature, and five times less than a conventional activated sludge plant for a small town.

The category of noncomplex soluble wastewater can be split up into acidified and nonacidified, and all intermediate forms between [3]. Considering the group of nonacidified soluble wastewater, some researchers or engineers have the opinion that the installation of a separate acidogenic reactor would be profitable, because of the presumed higher overall process stability and the much higher space (sludge) loading rates that can be accommodated in the second – methanogenic reactor [3]. We wanted to use a cascade arrangement in the ABR for treating nonacidified wastewater.

In our previous works [4, 5] we have studied the behaviour of an anaerobic baffled reactor (ABR) treating easy acidifying wastewater. From these works followed that ABR is not very adequate for treating easy acidifying wastewater. The cascade arrangement in ABR can cause the segregation of individual anaerobic process phases (hydrolysis, acidogenesis, acetogenesis, and methanogenesis).

It allows the volatile fatty acids (VFA) accumulation in the first compartments and can lead to a situation when the rate of the acetic acid influx into the next compartments will be higher than the rate of its conversion into methane. This brings a decrease in pH values in the baffled reactor whereas at pH under 6.5 the methanogenic process is strongly inhibited. If this situation occurs, it is necessary to adjust the pH by an emergency addition of a proper base, preferably NaHCO$_3$.

In the work [4], the highest reached organic loading

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was 15 kg m^{-3} d^{-1}, but high doses of NaHCO$_3$ (m(Na-HCO$_3$)/m(COD) = 1) were influxed into reactor. In this work, the performance of an ABR and an UASB reactor is compared, both reactors belong to the group of high-rate anaerobic reactors with a sludge bed. The reactors were operated under the same conditions with the same nonacidified feed.

EXPERIMENTAL

The construction of laboratory models of the ABR and the UASB reactor is shown in Fig. 1. The models were made of plexiglass. The size of the ABR was: length 43 cm, width 13 cm, height 30 cm. Useful volume of the reactor was 13.05 dm^3. A proper construction of the baffles allowed wastewater to flow through the sludge bed from bottom up. The distance of the upper edge of the baffles between the ascending and descending compartments from the water level was about 1 cm. The UASB reactor was made from a tube with an inside diame-

ter of 10 cm and the volume of this reactor was 3.7 dm^3.

The hydraulic characteristic of the reactor has been described in work [4]. The value of the dispersion number determined for the used ABR laboratory model was $D/(uL) = 0.0788$, for UASB reactor it was $D/(uL) = 0.1358$.

The dispersion value for ABR was $\sigma^2 = 0.1451$ and the theoretical number of ideally mixed tanks $N = 6.89$. For the UASB reactor the dispersion value was $\sigma^2 = 0.2511$ and the theoretical number of ideally mixed tanks $N = 3.96$. These results regarding the ABR are very similar to those obtained by *Grobicki* and *Stuckey* [6] for an ABR with four compartments and similar hydraulic retention time (50—60 h).

In this work, two types of synthetic wastewater were used containing:

1. Starch and peptone, NaHCO$_3$ (m(NaHCO$_3$)/m(COD) = max 0.5) and nutrients (nitrogen and phosphorus). Two concentrations of COD 6000 mg dm^{-3} and 2000 mg dm^{-3} were used.
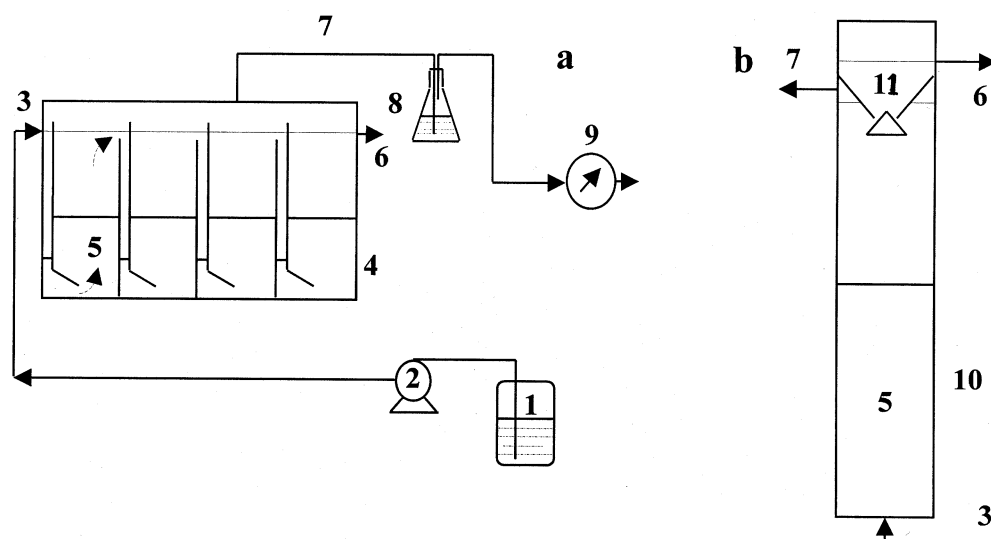
Fig. 1. Laboratory models of the ABR (*a*) and the UASB (*b*) reactor. *1.* Synthetic wastewater, *2.* peristaltic pump, *3.* influent, *4.* ABR vessel, *5.* sludge bed, *6.* effluent, *7.* biogas outlet, *8.* 4 M solution of NaOH, *9.* methane production measurement, *10.* UASB reactor vessel, *11.* g—l—s separator.

Table 1. Synthetic Wastewater Composition

Component	Concentration/(g dm^{-3})		
	ρ(COD) 6000 mg dm^{-3}	ρ(COD) 2000 mg dm^{-3}	ρ(COD) 4000—15 000 mg dm^{-3}
Starch	4.5	1.5	–
Peptone	1.0	0.33	–
HEC	–	–	3.5—13.13
NaHCO$_3$	max 3.0	max 1.0	–
N—NH$_4$	0.079	0.027	0.053—0.198
P—PO$_4$	0.016	0.005	0.013—0.041
CaCl$_2$	0.083	0.028	0.056—0.21
MgSO$_4 \cdot$ 7H$_2$O	0.152	0.051	0.102—0.38

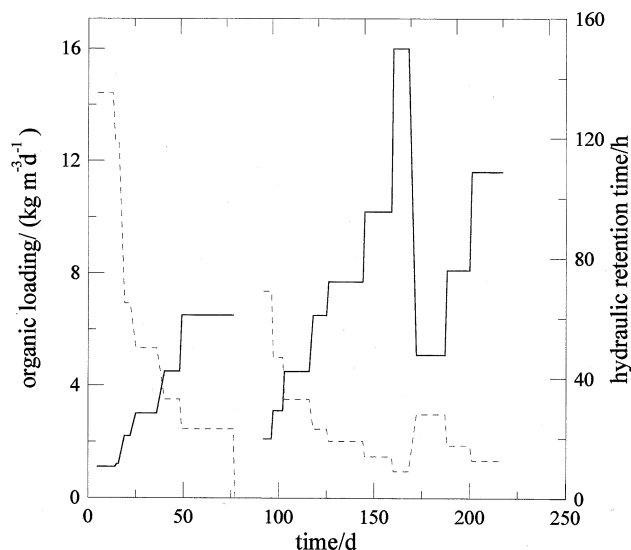**Fig. 2.** Course of the organic loading and hydraulic retention time using starch as substrate. $\rho(COD)$ 6000 mg dm^{-3}; —— B_V, – – – HRT.

Fig. 3. Concentration of COD in the ABR effluent using starch as substrate. $\rho(COD)$ 6000 mg dm^{-3}; ● filtered, ○ nonfiltered.

2. Hydroxyethylcellulose (HEC) and nutrients, $\rho(COD)$ was 4000—15 000 mg dm^{-3}.

The concentrations of nutrients added to the synthetic wastewater were chosen according to the ratio $\rho(COD):\rho(N):\rho(P) = 500:5:1$. As the wastewater was synthetic, micronutrients or trace elements [4] were added, too. The wastewater composition is shown in Table 1. The reactors were filled with anaerobically stabilized sludge from the Central Wastewater Treatment Plant Bratislava – Vrakuňa. The average volatile suspended solids (VSS) content of sludge was 18.2 g dm^{-3}.

The sludge amount used for the ABR inoculation was 7.4 dm^3, for the UASB reactor inoculation 2.1 dm^3 was used. The specific methanogenic activity $m(\text{methane}(COD))$ $m(VSS)^{-1}$ t^{-1} of the utilized sludge was 0.072 kg kg^{-1} d^{-1}. Starch and peptone were used for the determination of specific activity with the same feed composition as the one used at the operation of the reactors (Table 1). The wastewater was pumped into the reactors with peristaltic pumps. The biogas from the reactors was bubbled through a 4 mol dm^{-3} solution of NaOH (entrapment of CO$_2$ and H$_2$S) and subsequently the amount of produced CH$_4$ was measured. Reactors were operated at 37 °C.

The investigation of the function of the reactors consisted in a gradual increase of the organic loading and observing their response. The $\rho(COD)$, pH, the concentration of VFA, suspended solids, and biogas production were measured in the influxed wastewater, in the reactor and in the outlet. All the analyses were accomplished by the standard methods [7]. Isotachophoresis was used for the measurement of VFA [8], while the titrimetric method of *Kapp* [9] was used to determine the total amount of VFA.
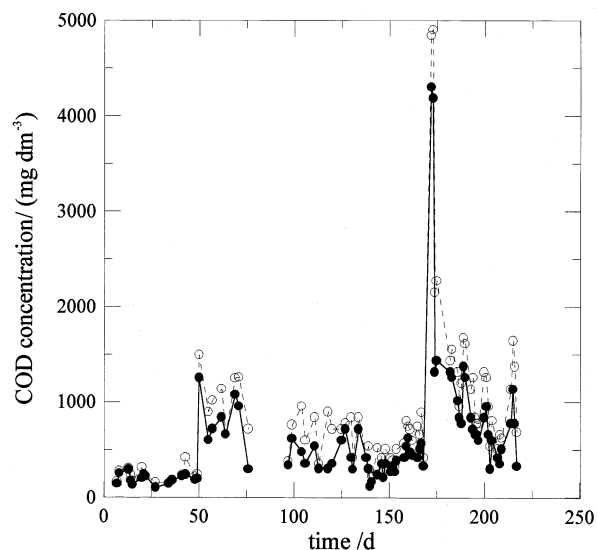

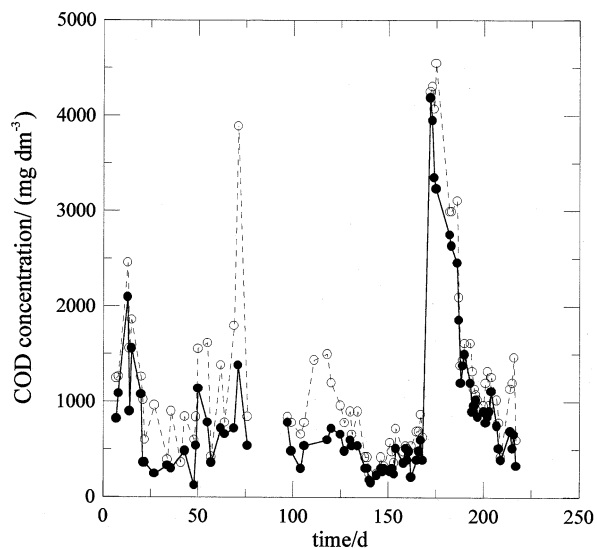**Fig. 4.** Concentration of COD in the UASB reactor effluent using starch as substrate. $\rho(COD)$ 6000 mg dm^{-3}; ● filtered, ○ nonfiltered.

RESULTS AND DISCUSSION

As it was mentioned above, the behaviour of reactors was observed during a gradual increase of the organic loading. The concentration of starch synthetic wastewater was constant, 6000 mg dm^{-3} and 2000 mg dm^{-3}. The organic loading (B_V) was increased by increasing the substrate flow-rate. The courses of organic loading and hydraulic retention time (HRT) are in Fig. 2. When the substrate that contained starch and peptone was used ($\rho(COD)$ 6000 mg dm^{-3}) the maximum organic loading was 15 kg m^{-3} d^{-1}. The
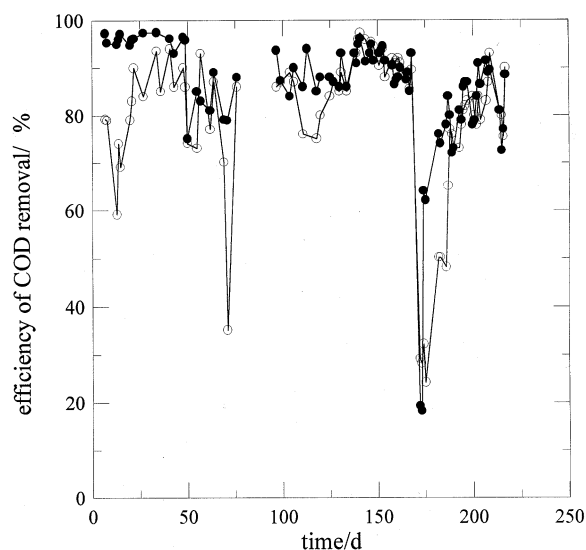
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Fig. 5. COD removal efficiency in the ABR and the UASB reactor using starch as substrate. $\rho(COD)$ 6000 mg dm^{-3}; ● ABR, ○ UASB.

initial organic loading was 1.1 kg m^{-3} d^{-1}. The concentrations of filtered and nonfiltered COD in effluent from the ABR are in Fig. 3, and those in the UASB reactor effluent are in Fig. 4. It is evident from Fig. 3 that up to an organic loading 6.5 kg m^{-3} d^{-1} (50 days after start up) the COD concentration in the ABR effluent was under 400 mg dm^{-3}, with minimal differences between the filtered and nonfiltered COD. The $\rho(COD)$ in the UASB reactor effluent was higher in this period. Even the values above 1000 mg dm^{-3} were reached. Much higher, 200—2000 mg dm^{-3}, was the difference between the filtered and nonfiltered COD (Fig. 4).

The efficiencies in the ABR in this period were more than 90 % (Fig. 5). The performance of the UASB reactor during 50 d after start up was unstable, the efficiency decreased also under 80 % (Fig. 5). Initial biomass granulation in the ABR was observed after 35 days of performance at a B_V of about 3 kg m^{-3} d^{-1} and after 60 days of performance at a B_V of about 6.5 kg m^{-3} d^{-1} in the UASB reactor. This difference of the biomass granulation rate was discussed in the work [5].

One explanation can be the kinetic selection of filamentous bacteria of the *Methanotrix* sp. under high acetate concentration (over 1.5 g dm^{-3}), as described by *Morvai et al.* [10]. This measurement achieved faster granulation in the ABR compared to the UASB reactor. 76 d after start up, the reactors were turned off for 14 d. After three weeks from the new start up, the organic loading reached again 6.5 kg m^{-3} d^{-1}. In this period, the difference between the filtered and nonfiltered COD in the UASB reactor effluent increased.

In the period between approximately 125 d and 170 d of the operation both reactors presented a good

stability with minimal difference between the filtered and nonfiltered COD in the effluents (Figs. 3 and 4). The efficiency of COD removal was about 70—85 % (Fig. 5). On the 170th day, the reactors were turned off for one day (B_V was 15 kg m^{-3} d^{-1}) for technical reasons. It was assumed that as the period of turning off was short, starting up with $B_V = 15$ kg m^{-3} d^{-1} would not cause problems. The response to this turning off and starting up can be seen in Figs. 3—5.

The pH in the ABR compartments gradually decreased to 6, in the effluent from UASB reactor even to 5. The methanogenesis was inhibited, the COD concentration in the individual compartments of ABR increased, as well as in the effluents from ABR and UASB reactor.

Also the VFA concentration in effluent from both reactors significantly increased. One explanation of this failure can be as follows. At this B_V (15 kg m^{-3} d^{-1}), both the production of biogas and the loading of sludge bed were high. The resulting expansion of sludge bed was primarily caused by the high biogas production, not by the hydraulic loading. The expansion was about 300 %, that means that the sludge bed was three times higher than after the turning off and following turning on of reactors. In the expanded sludge bed, intensive mass transfer took place between the main flow of liquid and the granular biomass, which supported methanogenesis. The enhanced biogas production supports mixing in the sludge bed. When the reactor started at high $B_V = 15$ kg m^{-3} d^{-1} after one day out of operation, sludge beds did not expand and immediately were overloaded, pH in reactors decreased and methanogenesis was inhibited. As shown in Figs. 3 and 4, the ABR overcame the effect of failure faster than UASB reactor. Considerable differences between the performance of these reactors were not observed. It was assumed that at high B_V and using a nonacidified wastewater hydrolysis and acidogenesis should be faster in the ABR than in the UASB reactor. At an organic loading of 15 kg m^{-3} d^{-1}, the hydraulic retention time was 9.6 h and it was a sufficient time for hydrolysis and acidogenesis in the UASB reactor.

Therefore, in further investigations, we compared the performance of these two reactors using a diluted substrate ($\rho(COD)$ 2000 mg dm^{-3}), reaching thus a lower hydraulic retention time. The maximum organic loading at $\rho(COD)$ 2000 mg dm^{-3} was 12 kg m^{-3} d^{-1} and the minimal hydraulic retention time was 4 h. The organic loading (B_V) increased by increasing the substrate flow-rate (Fig. 6). The average, minimal, and maximal concentrations of COD in the effluent from ABR were 158.9 mg dm^{-3}, 41.8 mg dm^{-3}, and 311 mg dm^{-3}, respectively (Fig. 7).

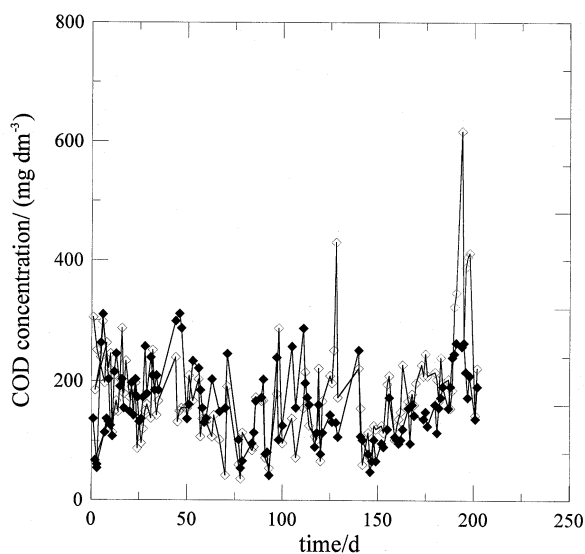In the UASB reactor effluent, the average $\rho(COD)$ was 179 mg dm^{-3}, minimal 36 mg dm^{-3}, and maximal 617 mg dm^{-3} (Fig. 7). The average efficiencies of the ABR and UASB reactor were 92 % and 91 %,
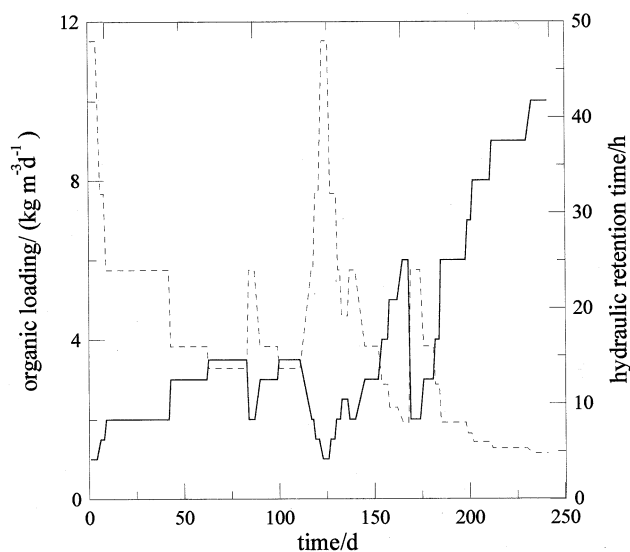
Fig. 6. Course of organic loading and hydraulic retention time using starch as substrate. ρ(COD) 2000 mg dm^{-3}; —— B_V, – – – HRT.
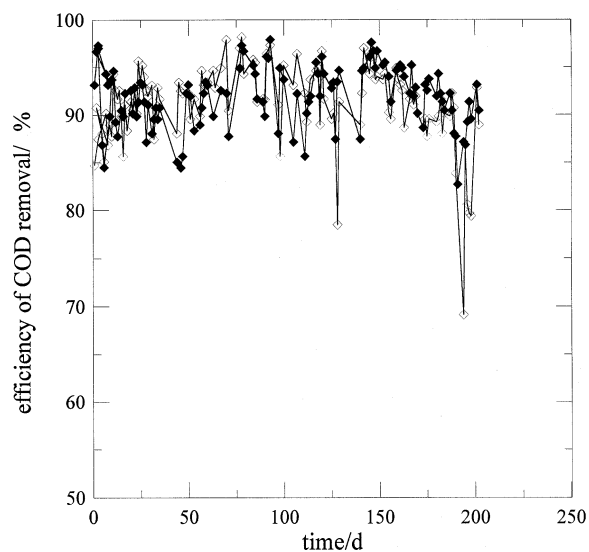
Fig. 8. COD removal efficiency in the ABR and the UASB reactor using starch as substrate. ρ(COD) 2000 mg dm^{-3}; ◆ ABR, ◇ UASB.

Fig. 7. Concentration of COD in the ABR effluent and UASB reactor using starch as substrate. ρ(COD) 2000 mg dm^{-3}; ◆ ABR, ◇ UASB.

respectively (Fig. 8). These results did not represent significant differences in the performance of ABR and UASB reactor. COD removal efficiencies in the individual compartments of the ABR are in Table 2. The major part of COD was removed in the first and the second ABR compartment, it corresponds to the maximal methanogenic rate in these compartments.

The pH in the ABR rose from the first to the last compartment. The average pH in the first compartment was 6.4, this indicates that the most intensive acidification took place there. In the other compartments the average pH's were 6.8, 6.9, 7.0. During the

operation of the reactors, the concentrations of volatile fatty acids (VFA) in the reactors were determined by a titration method [9] and by isotachophoretic measurements [8]. The concentration of VFA in the first compartment at higher B_V was about 1500 mg dm^{-3}. It follows that this concentration of VFA did not inhibit methanogenic process. The isotachophoretic measurements confirmed that acetic acid was the major component of VFA. The average concentrations of VFA in individual compartments of ABR and UASB reactor at $B_V = 15$ kg m^{-3} d^{-1} (ρ(COD) 6000 mg dm^{-3}) and at $B_V = 10$ kg m^{-3} d^{-1} (ρ(COD) 2000 mg dm^{-3}) are summarized in Tables 3 and 4. These concentrations were calculated for the COD and fraction of acidified COD which is shown in Tables 3 and 4. For easy acidifying wastewater, the fraction of acidified COD in individual compartments of ABR was very high and it might cause problems with methanogenesis [4]. In this work, it was considerably lower with respect to the substrate used.

The fractions of acidified COD were similar for both substrates concentrations (ρ(COD) 6000 mg dm^{-3} and 2000 mg dm^{-3}). They were about 70 % in the first compartment and about 30 % in the last compartment.

During the operation, the tests of methanogenic and nonmethanogenic activities were realized [11]. It was evident from the results that the methanogenic phase was the rate-limiting step in the anaerobic degradation of used substrates. The determined specific hydrolytic activity was high in the first compartment of ABR, 36 g g^{-1} d^{-1} m(substrate(COD)) m(VSS)$^{-1}$ t^{-1} [11]. In the UASB reactor, the rates of hydrolysis (3.52 g g^{-1} d^{-1}) and acidogenesis (1.12 g g^{-1} d^{-1}) were lower. A considerably higher rate of

Table 2. COD Removal Efficiency in the Individual Compartments of the ABR for Starch and HEC Substrates

Compartment	Average efficiency/%		
	Starch + peptone ρ(COD) 6000 mg dm^{-3}	Starch + peptone ρ(COD) 2000 mg dm^{-3}	HEC ρ(COD) 4000—15000 mg dm^{-3}
1	58.3	48.3	27.95
2	40.3	54.5	11.2
3	31.9	37.1	8.01
4	29.6	21.3	4.45

Table 3. Average Concentrations of VFA in the Individual Compartments of the ABR and the UASB Reactor and the Fraction of Acidified COD at $B_V = 15$ kg m^{-3} d^{-1} (ρ(COD) 6000 mg dm^{-3})

| Acid	c/(mmol dm^{-3})				UASB
	Individual compartments of ABR				
	1	2	3	4	
Formic	5.46	0.84	0.095	0.048	0.048
L-Lactic	3.09	0.99	0.25	0.27	0.17
Acetic	9.98	4.46	0.79	0.21	0.52
Propionic	2.86	2.29	0.45	0.067	0.38
Butyric	5.58	2.52	0.27	0.023	0.078
Valeric	0.30	0.26	0.065	0.017	0.11
Σ VFA	27.27	12.20	1.197	0.632	1.231
$\Sigma\rho$(COD—VFA)/(mg dm^{-3})	2300	1106	184	55	128
Fraction of acidified COD/%	70.4	53.4	20.6	10.5	29.3

Table 4. Average Concentrations of VFA in the Individual Compartments of the ABR and the UASB Reactor and the Fraction of Acidified COD at $B_V = 10$ kg m^{-3} d^{-1} (ρ(COD) 2000 mg dm^{-3})

| Acid	c/(mmol dm^{-3})				UASB
	Individual compartments of ABR				
	1	2	3	4	
Formic	2.00	1.03	0.17	0.11	0.17
L-Lactic	3.49	1.22	0.31	0.22	0.26
Acetic	2.87	2.51	0.43	0.13	0.069
Propionic	1.17	1.87	0.03	0.03	0.064
Butyric	0.77	–	–	–	–
Valeric	–	–	–	–	–
Σ VFA	10.3	9.69	1.08	0.49	0.57
$\Sigma\rho$(COD—VFA)/(mg dm^{-3})	804.2	503.6	34.7	34.3	38.5
Fraction of acidified COD/%	68.6	49.7	10.7	10.2	30.7

hydrolysis was obtained for the granular biomass from the ABR compared to the granular biomass from the UASB reactor. However, the rates of hydrolysis and acidogenesis in the UASB reactor were sufficient and higher than the rates of methanogenesis (1.5 g g^{-1} d^{-1} – ABR, 0.7 g g^{-1} d^{-1} – UASB reactor). Therefore any significant difference between ABR and UASB reactor performance was not observed.

In further investigations hydroxyethylcellulose (HEC) was used, which was assumed to be a more convenient substrate for the demonstration of ABR advantages. Therefore, a substrate that contained HEC

was used. ABR and UASB reactor were filled with granular sludge from the previous experiment. The concentration of inoculum was the same in ABR and UASB reactor (21.6 g dm^{-3} volatile suspended solids). Already the first experiences with this substrate showed that it was not necessary to add NaHCO$_3$ to adjust the pH in the reactors. The maximum organic loading was 5 kg m^{-3} d^{-1}. The efficiency of COD removal was lower, so the hydraulic retention time was prolonged to 240 h. The course of COD concentration is in Fig. 9. The ρ(COD) of the influent was in the range of 4000—15 000 mg dm^{-3}.
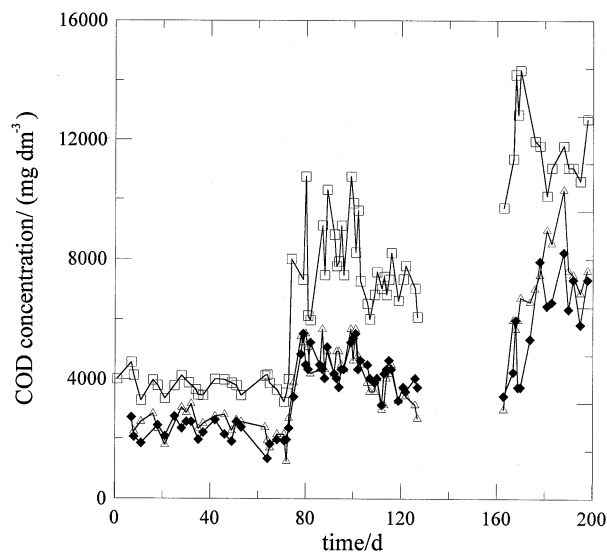
Fig. 9. Concentration of COD in influent and effluents of the ABR and the UASB reactor by using HEC as substrate. $\rho(COD)$ 4000—15 000 mg dm^{-3}; □ influent, ◆ ABR, △ UASB.
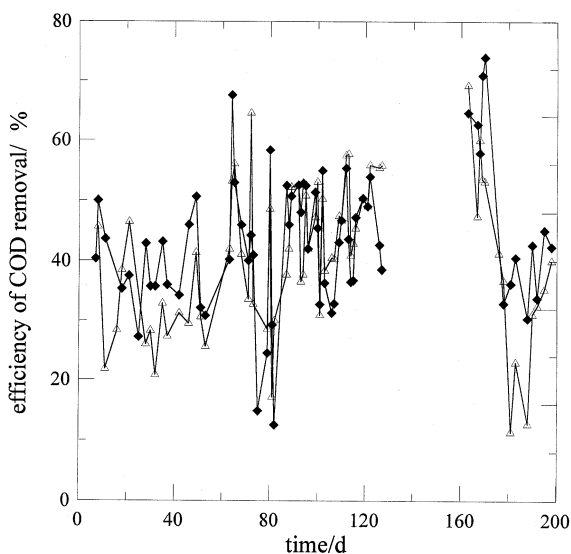
Fig. 10. COD removal efficiency in the ABR and the UASB reactor using HEC as substrate. $\rho(COD)$ 4000—15 000 mg dm^{-3}; ◆ ABR, △ UASB.

Table 5. Activities in the Individual Compartments of ABR for HEC Substrate

	Activity/(g g^{-1} d^{-1})			
	Individual compartments of ABR			
	1	2	3	4
Hydrolytic	2.6	2.2	1.7	2.4
Acidogenic	5.5	3.7	2.2	2.9
Methanogenic	1.09	1.09	1.11	0.62
$\rho(VSS)/(g\ dm^{-3})$	1.06	1.54	2.50	1.29

The average $\rho(COD)$ of the ABR effluent was 3972.5 mg dm^{-3}, its maximal value was 8220 mg dm^{-3} and the minimal one 1345 mg dm^{-3} (Fig. 9). The average $\rho(COD)$ of UASB reactor effluent was 4307.1 mg dm^{-3}, maximal value was 10 312 mg dm^{-3} and the minimal one 1255 mg dm^{-3} (Fig. 9).

The efficiency of COD removal is shown in Fig. 10. Its average value in ABR was 43 %, maximal efficiency was 74 % and minimal efficiency 12 % (Fig. 10). The

average efficiency of the COD removal in the UASB reactor was 41 %, the maximal one 69 %, and the minimal one 11 % (Fig. 10). During the operation, the differences between the performance of ABR and UASB reactor were not observed. As with starch wastewater, the majority of COD removal occurred in the first compartment of ABR (Table 2). The pH was not adjusted and negligible gradients of pH were observed in comparison to the starch substrate. The average pH in the ABR was 6.8. The substrate (HEC) was only partly acidified. This is evident also from the fraction of acidification which was 1.8 %. Similarly as in the case of starch substrate, the tests of methanogenic and nonmethanogenic activities were realized. At a B_V of 3.5 kg m^{-3} d^{-1}, the sludge from individual compartments of the ABR was taken out. For the determination of hydrolytic activity, HEC ($\rho = 1.5$ g dm^{-3}) was used, for the acidogenic activity glucose (2 g dm^{-3}) was used. The pH was adjusted by the addition of NaHCO$_3$ (1 g dm^{-3}). The tests of methanogenic activity were realized utilizing sodium acetate ($\rho = 2$ g dm^{-3}). The hydrolytic and acidogenic activities were determined as the maximum consumption rate of utilized substrate, expressed as mass of COD per mass of sludge VSS per day [11]. These activities are shown in Table 5.

In comparison to the starch substrate, mainly the rates of hydrolysis and acidogenesis in the first compartment were significantly lower, 2.6 g g^{-1} d^{-1} and 5.5 g g^{-1} d^{-1}, respectively. In the work [12], the authors mentioned that the resistance of enzymatic degradation of HEC depends on its relative molecular mass and degree of substitution. The response of enzymatic degradation rises with the degree of substitution. For our experiment, only a waste HEC was available (used as an additive for the improvement of hydraulic transport). The relative molecular mass of this HEC was 40 000—60 000. We did not know the degree of substitution, but it can be assumed that it was low. In the case of HEC it is probable that the results of biochemical degradation are better with a higher degree of substitution.

CONCLUSION

A cascade arrangement in the ABR is ideal for the segregation of phases of anaerobic processes, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. It followed from the results of the previous work that the ABR is not very suitable for the treatment of acidified wastewater. The ABR is, however, convenient for the treatment of nonacidified wastewater. When nonacidified substrate containing starch and peptone was used, methanogenesis was the limiting step in anaerobic degradation. A considerably higher rate of hydrolysis was obtained for the granular biomass from the ABR compared to the granular biomass from the UASB reactor. However, the rates of hydrolysis and acidogenesis in the UASB reactor were sufficient and higher than the rates of methanogenesis.

Therefore any significant difference between ABR and UASB reactor performance was not observed. It was confirmed that a faster granulation occurred in the ABR than in the UASB reactor. The reactor performance using HEC and tests of methanogenic and nonmethanogenic activity showed that HEC is a slowly degradable substrate.

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