Behaviour of Anaerobic Baffled Reactor Treating Partly Acidified or Easy Acidifying Wastewater

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Partly acidified wastewater has been treated in an anaerobic baffled reactor (ABR) that belongs to high-rate anaerobic reactors. The running processes as well as the granular biomass cultivation were observed in the present work. The wastewater contained sodium acetate, D-glucose, macro- and micronutrients. Sodium bicarbonate was used for adjusting the pH in the reactor. The response to step increasing of the organic loading rate was observed by measuring the filtered as well as unfiltered COD in the reactor effluent, the concentrations of volatile fatty acids, and the pH in each ABR compartment. An anaerobic granular biomass was cultivated in the reactor and organic loading rate of 15 kg m^{-3} d^{-1} was reached. It can be inferred from the results of this work that for acidified wastewater the granulation process in ABR is more sensitive than in other types of high-rate anaerobic reactors, for example, in UASB reactor or in a hybrid reactor.

The anaerobic baffled reactor (ABR) belongs to high-rate anaerobic reactors and it represents a modification of the reactor with a sludge bed. This type of reactor was described for the first time in the paper [1]. In the ABR the mixture of the anaerobic culture of microorganisms is divided into compartments separated mostly by vertical baffles. Thus a simple construction of cascade of reactors with a sludge bed is formed. The ABR when duly operated allows a high reaction rate per unit volume of the reactor. Paper [2] serves as an example of how high the loading rate of the ABR can be. Using synthetic wastewaters that contained bactopeptone and sucrose, the authors of the work reached an organic loading of 36 kg m^{-3} d^{-1} (COD) at a hydraulic residence time of 4.8 h. The reached velocity of the substrate removal was 24 kg m^{-3} d^{-1} and the efficiency of the COD removal with this load came to 60 %. The 91 % efficiency of the COD removal was gained as early as at 11.4 kg m^{-3} d^{-1} The ABR performance was also the subject of the works of *Grobicki* and *Stuckey* [3, 4]. In the first of the works the authors describe the hydraulic characteristics of baffled reactors with 4, 6, and 8 compartments, respectively. These characteristics were measured in pure water (without biomass) with fluorescein as a tracer, in the presence of biomass wherein lithium chloride served as a tracer. These measurements led to the following interesting result: within a hydraulic residence time of 4—80 h minimum differences in the dispersion figures were measured. Paper [3] contains a description of the ABR in stable conditions as well as the conditions of a shock load where peptone or sucrose and peptone, respectively, were used as the substrate. The ABR adaptation ability is illustrated by an experiment wherein at a load of 4.8 kg m^{-3} d^{-1} (COD) and a residence time of 20 h (efficiency of COD removal being 98 %) the hydraulic residence time was reduced to 1 h. The shock lasted 3 h and with an unchanged substrate concentration it represented a loading of 96 kg m^{-3} d^{-1} Immediately after this shock load a dramatic decrease of the treatment process efficiency occurred and the biomass wash-out increased from 75 mg dm^{-3} to 350 mg dm^{-3} Within 24 h the reactor parameters returned to the state before the shock load.

The hydraulic conditions in a laboratory ABR are dealt with in the work of *Nachaiyasit* and *Stuckey* [5] as well. The authors investigated the influence of changing the recycle of treated water on the reactor performance with the other parameters being unchanged. With the recirculation ratio increase changing from 0 to 2.0 a slight decrease of the treatment efficiency was observed (COD from 99 % to 96 %) whereas the buffering capacity of the system increased. The influence of the recycle was most distinctly manifested in the biogas structure. The methane content decreased from 73 % to 64 %.

Grobicki and *Stuckey* [6] also investigated formation and consumption of volatile fatty acids in an ABR under stable conditions and under the conditions of the shock load as well. Above all they have pointed out the important role that the formic acid plays as an indicator of the unstable conditions of the shock load.

An ABR was also used in the process of the anaerobic-aerobic treatment of wastewater with nutrient removal [7]. The first and second compartments were anaerobic, the third one was anoxic and the fourth one was reduced – it served to separate the biomass that was recirculated to the beginning of the ABR. The load of the anaerobic part was relatively low: 2.17 kg m^{-3} d^{-1} (COD). The system was patented in Italy under the name ANANOX®

It is known from literature that also a baffled anaerobic reactor has been used in combination with a layer of the carrier – a hybrid anaerobic baffled reactor – HABR. This type of reactor was subject of the study of *Boopathy* and his colleagues [8—10]. They detected the possibilities of molasses wastewater treatment. They dealt with concentrated wastewater having a COD over 100 g dm^{-3} while with an organic load of $B_v = 20$ kg m^{-3} d^{-1} and a hydraulic detention time of 3 d the reached removal efficiency of the COD was over 70 %. The carrier layer in all the three sections of HABR allowed quicker reactor loading than it is possible in a classical ABR or UASB. The initial organic loading was 4.3 kg m^{-3} d^{-1}. After 30 d it was 10.3 kg m^{-3} d^{-1}, after next 20 d it came to 20 kg m^{-3} d^{-1} and after two weeks the volumetric load increased to 28 kg m^{-3} d^{-1}

In the present work the main attention is directed to a detailed description of the operations going on in the course of the process of a granular anaerobic biomass cultivation on a partly acidified or easy acidifying substrate.

EXPERIMENTAL

The construction of a laboratory model of the anaerobic baffled reactor is clear from Fig. 1. The model was made of plexiglass and its proportions were as follows: length 43 cm, width 13 cm, height 30 cm. Reactor useful volume was 13.05 dm^{-3} The proper construction of the baffles allowed a wastewater 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 hydraulic characteristic of the ABR, *i.e.* the distribution of the residence time in the reactor was performed in the reactor without the biomass through an impulse change of the concentration of the tracer. Only an influx of the distilled water was led into the reactor. The KCl was used as a tracer. The KCl concentration in the outlet of reactor was measured conductometrically after the prior determination of the dependence of the KCl solution conductivity on its concentration in distilled water.

The reactor was filled with anaerobically stabilized sludge from the Central Wastewater Treatment Plant Bratislava-Vrakuňa. The sludge amount used for the reactor inoculation was 5 dm^{-3} with volatile suspended solids concentration (VSS) being 29.4 g dm^{-3} and its specific methanogenic activity 0.066 kg kg^{-1} d^{-1} m (methane COD)(m VSS)$^{-1}$ t^{-1}

The synthetic wastewater contained sodium acetate, D-glucose, $NaHCO_3$, and nutrients (nitrogen and phosphorus). The mass ratio of sodium acetate glucose was approximately 0.77 whereas their concentration was increasing according to the required load (COD of substrate varied in the range of 430—6000 mg dm^{-3}). The organic loading was also increased through changing the wastewater flow. The wastewater composition at the COD of 6000 mg dm^{-3} is

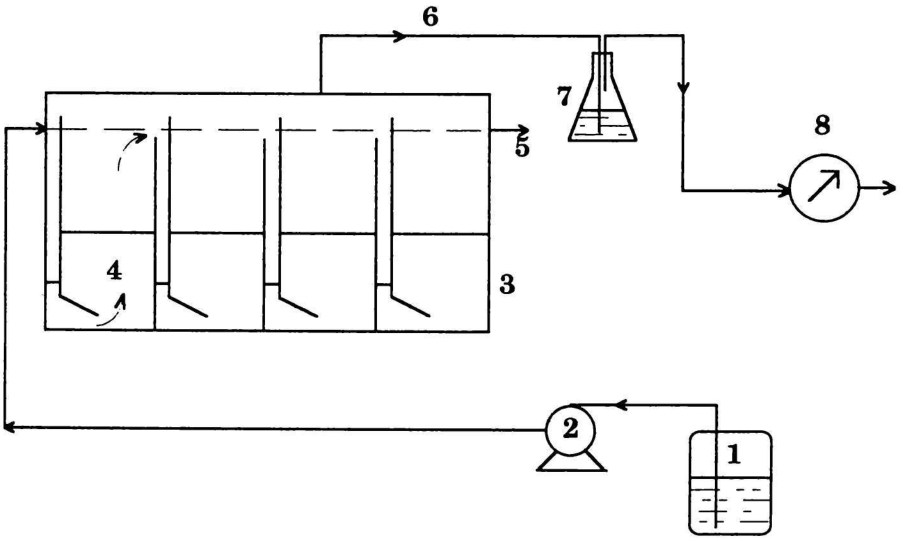

Fig. 1. Laboratory model of anaerobic baffled reactor: *1.* model wastewater container, *2.* peristaltic pump, *3.* ABR, *4.* sludge bed, *5.* effluent, *6.* biogas draw-off, *7.* 4 M-NaOH, *8.* methane production measurement.

Table 1. Synthetic Wastewater Composition (COD of 6000 mg dm^{-3})

Component	Concentration g dm^{-3}
Sodium acetate	3.19
D-Glucose	4.21
$NaHCO_3$	6.0
N (as NH_4^+)	0.0792
P (as PO_4^{3-})	0.0161
$CaCl_2$	0.083
$MgSO_4$ $7H_2O$	0.152

Table 2. Composition of the Trace Elements Stock Solution

Component	Concentration g dm^{-3}
$FeCl_3 \cdot 4H_2O$	2000
$CoCl_2 \cdot 6H_2O$	2000
$MnCl_2 \cdot 4H_2O$	500
$CuCl_2$ $2H_2O$	30
$ZnCl_2$	50
H_3BO_3	50
$(NH_4)_6Mo_7O_2 \cdot 4H_2O$	90
Na_2SeO_3 H_2O	100
$NiCl_2 \cdot 6H_2O$	50
EDTA	1000
Resazurin	500
HCl 36 %	1 cm^3 dm^{-3}

shown in Table 1. Because used wastewater was synthetic, micronutrients or trace elements were added, too. Composition of the trace elements stock solution is shown in Table 2. The amount of 2 cm^3 to 1 dm^3 of the synthetic wastewater (COD 6000 mg dm^{-3}) was dosed from this solution. $NaHCO_3$ was added in the maximum amount of 1 g to 1 g of the substrate COD.

The wastewater was pumped into the reactor with a peristaltic pump. The biogas being generated was led through 4 M-NaOH in which it was trapped, especially CO_2 and H_2S and measurement of the produced methane followed afterwards. Measurements were carried out at 37 °C. Investigation of the baffled reactor function consisted in a gradual increase of the organic loading and observing this increase response. The COD, pH, the volatile fatty acids concentration (VFA), suspended solids concentration, and biogas production were among the most important values being investigated in the influxed wastewater, in the reactor, and in the outlet. All the analyses were accomplished by the standard methods [11] (except of VFA analyses).

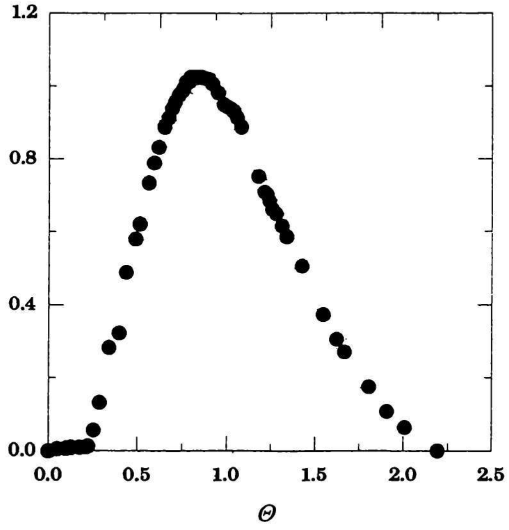

Fig. 2. Hydraulic characteristic of the used laboratory model of ABR.

RESULTS AND DISCUSSION

Hydraulic Characteristic of the ABR Used

As it is already presented in the experimental part of the work the hydraulic characteristic was determined in the ABR without biomass. The measured distribution of the residence time in the reactor outlet is shown in Fig. 2, which represents the so-called C curve. The variable θ is a reduced (dimensionless) time

$$\theta = \frac{t}{\bar{t}}$$

where t is the residence time and $\bar{t}$ is the mean (or theoretical) residence time in the reactor.

Variable C expresses the ratio $C = c/c_0$, where c is the tracer concentration in the outlet and c_0 is concentration that is obtainable when the additional amount of the tracer (m) is dispersed throughout the entire reactor volume.

To characterize the residence time distribution the mean value of distribution μ that is defined by the general equation

$$\mu = \frac{\int_0^\infty x f(x)\mathrm{d}x}{\int_0^\infty f(x)\mathrm{d}x}$$

as well as the dispersion σ_x^2 defined by the equation

$$\sigma_x^2 = \frac{\int_0^\infty (x-\mu)^2 f(x)\mathrm{d}x}{\int_0^\infty f(x)\mathrm{d}x}$$

were used.

The trapezium rule can be used with satisfactory accuracy to calculate these integrals. The mean value for this case of distribution is

$$\bar{t}_c = \frac{\int_0^\infty t f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t}$$

and the dispersion

$$\sigma_t^2 = \frac{\int_0^\infty (t-\bar{t}_c)^2 f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t} = \frac{\int_0^\infty t^2 f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t} - \bar{t}_c^2$$

Besides the C curve the system is characterized by the dispersion number (D/uL) and theoretical number of ideally mixed reactors (N) of an equal size connected in series which as to their performance would correspond to the system investigated. The C curve, being known N, will be determined as the reciprocal value of the dispersion σ^2 For hydraulically closed systems the dispersion σ^2 is calculated from the relation

$$\sigma^2 = \frac{\sigma_t^2}{\bar{t}_c^2} = 2\frac{D}{uL} - 2\left(\frac{D}{uL}\right)^2 (1 - \mathrm{e}^{uL/D})$$

where D is axial dispersion coefficient, u the mean flow velocity through the reactor, and L length of the tank.

The determined value of the dispersion number for used ABR laboratory model was $D/uL = 0.0788$, the dispersion value $\sigma^2 = 0.1451$, and theoretical number of ideally mixed tanks $N = 6.89$. These results are very similar to those which were obtained in the work of *Grobicki* and *Stuckey* [4] for ABR with four compartments.

First Start-Up of ABR

As it was mentioned above, the behaviour of the ABR consisted in a gradual increase of the organic loading and response to this increase. The initial organic loading was 0.2 kg m^{-3} d^{-1} The other parameters of ABR with this load were as follows: the flow of a synthetic wastewater $Q = 5.76$ dm^3 d^{-1} which corresponded to the hydraulic residence time $\Theta = 2.3$ d, COD of wastewater was 430 mg dm^{-3} The next course of the organic loading and the hydraulic residence time are shown in Fig. 3. Hydraulic residence time corresponds with the flow rate of wastewater

$$\Theta = \frac{V}{Q}$$

where V is the reactor volume and Q the wastewater flow rate.

Step changes of the organic loading were realized by increasing the wastewater concentration (at the constant Θ) or by increasing the substrate flow rate (at the constant substrate concentration). From Fig. 3 it is evident that up to the load of approximately 1.6 kg m^{-3} d^{-1} B_v was being increased due to the substrate concentration increase at a constant residence time. After the first ABR loading the efficiency increased over 80 % in the course of several days which led to increasing B_v in relatively quick succession to the value of 0.4 kg m^{-3} d^{-1} or 0.8 kg m^{-3} d^{-1}, respectively. The fact was not visually manifested in the reactor performance (neither a more abrupt increase of the biogas production in the sludge bed was observed nor a leak of the suspended solids from the reactor was registered). However, the outlet concentration grew up as high as over 1000 mg dm^{-3} (Fig. 4) and removal efficiency of COD dropped under 50 % (Fig. 5). These intensive step changes were also manifested in lowering the pH values in all the four reactor compartments. Within 20 d the reactor performance got steady, the COD in the effluent dropped to 200 mg dm^{-3} and COD removal efficiency went up to 90 % (both the filtered and unfiltered COD). In this reactor state B_v was increased again by a higher value than the one recommended for a granulation process, *e.g.* in paper [12]. The step-rise recommended for B_v is 20—30 %. In this case a step increase higher than 60 % was made (39th day). As seen in Figs. 4 and 5, the

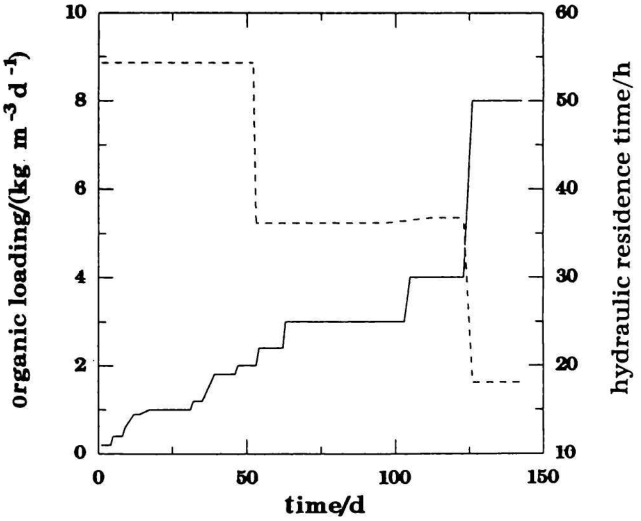

Fig. 3. Value course of organic loading and hydraulic residence time at the first start-up: —— B_v, - - - HRT.

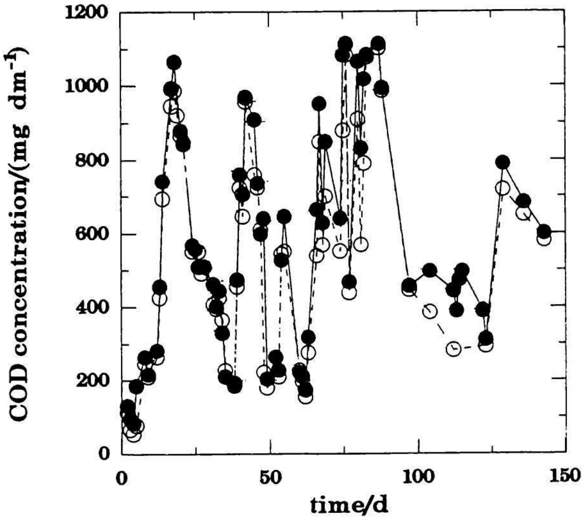

Fig. 4. Concentration of COD in the filtered (○) and unfiltered (●) effluent from ABR at the 1st start-up.

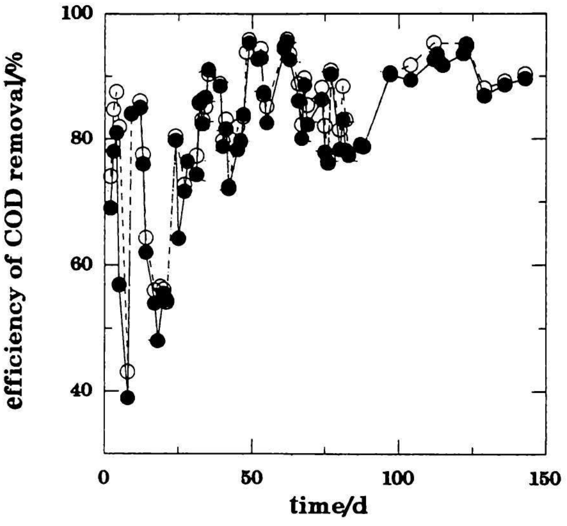

Fig. 5. Efficiency of COD removal at the 1st start-up, filtered (○) and unfiltered (●) effluent.

COD had again risen almost to 1000 mg dm^{-3} and the efficiency went down under 80 %, but 10 d later effluent COD dropped to original values. At that time we began to realize the following fact. In the case of ABR a visual observation of the reactor and sludge bed is not the same indicator of a change state as it is in the case with UASB reactor or an anaerobic hybrid reactor. For example, while in the case of the UASB reactor an increase of B_v brings about a biogas production increase that loads the only one sludge bed, in the case of the ABR the load with biogas if not evenly, but yet is divided (in our case) among four sludge beds. In spite of the fact that especially the first compartment is the most loaded one, concerning the height of the sludge bed the generated biogas does not cause such a high turbulence as all the sludge is concentrated in a single sludge bed. After the reactor activity became stable with B_v = 1.6 kg m^{-3} d^{-1}, when the outlet COD was approximately 200 mg dm^{-3} (the inlet one being about 3700 mg dm^{-3}) and the treatment efficiency reached over 90 %, B_v was increased through the flow increase to 7.92 dm^3 d^{-1}, thus the hydraulic residence time was reduced to about 1.6 d. Up to this jump the sludge level in the individual reactor compartments was relatively stable. This flow increase and the simultaneous B_v enhancement caused a dramatic rise of the sludge bed level in the first compartment as well as a slow increase of the sludge bed in the fourth compartment. It is to be said that the abrupt raise of the sludge bed in the first compartment did not bring about so much sludge wash-out from it since a considerable sludge amount had floated out. The floated out layer did not constitute a firm crust as seen in some anaerobic reactors (the so-called "sludge scum"), but black foam was formed. It was evident that the sludge in that layer "took part" in the treatment process. Having accomplished the B_v increase, it caused a permanent enhancement of a difference between the filtered and unfiltered COD in individual compartments above the sludge bed. A temporary increase of the difference between the filtered and unfiltered COD could also be observed in the previous step enhancement. After getting a stable state, however, this difference was reduced. At that time the first granular biomass aggregates were observed in the sludge beds of all compartments. With a view of a considerable sludge-layer decrease (especially in first compartments) the next increase of the B_v values was carried out through increasing the substrate concentration. During the whole period also the daily methane production was measured. Almost from the start of the ABR performance its increase was proportionate to the B_v increase. The average methane production was about 0.32 m^3 (approximately 0.82 kg COD CH_4) per 1 kg of the COD introduced. The average value of the anaerobic biomass yield coefficient calculated from the COD balance at that period was 0.1 dm^3

After a step change to the B_v being about 3 kg m^{-3} d^{-1}, the COD in the outlet increased gradually to 1000 mg dm^{-3}, at the pH in the first compartment being 6 or less. This stage lasted about two weeks and no tendency of an improvement was observed. In the last compartments the pH increased as high as over 7. At that time, in the reactor the recirculation of the water portion from the last compartment to the first one with the recirculation ratio R = 1 was established (the residence time of wastewater in the reactor was 36.2 h and for the mixture with recirculation it was 18.1 h). It was assumed that this would cause a more regular loading of all compartments as well as the pH increase in the first compartment leading to enhancing methanization. This assumption was confirmed. The COD in the outlet dropped below 300 mg dm^{-3} and the floating layer in the first compartment disappeared. The following B_v increase to 4 kg m^{-3} d^{-1} was hardly observed in the outlet COD. The reactor state, but above all the sludge beds with a fully granulated biomass led us to test shocking load – to double B_v increase by raising the wastewater flow. The wastewater residence time in the reactor thus dropped to 18.1 h and mixture residence time with recycling was decreased to 12 h. The system response was surprising. After increasing the B_v to 8 kg m^{-3} d^{-1} the COD in outlet temporarily increased to 800 mg dm^{-3}, yet it gradually dropped under 600 mg dm^{-3} whereas the reactor efficiency was over 90 %. Thus at this stage the reactor response to a high shock load was better than with an increase from 2.6—3 kg m^{-3} d^{-1} in a noncompletely granulated biomass. The theoretical value of the biomass yield coefficient at that stage was approximately 0.05.

During the operation of an ABR the concentrations of volatile fatty acids (VFA) in the reactor were determined partly by a titration method [13] and partly by isotachophoretic measurements [14]. The titration

Table 3. VFA Concentrations in Individual ABR Compartments 1—4

Acid	$c/(\mathrm{mmol\ dm^{-3}})$							
	Measurement I				Measurement II			
	1	2	3	4	1	2	3	4
Valeric	0.42	0.31	0.21	0.16	0.31	0.36	0.10	0.00
Butyric	3.50	1.70	0.71	0.38	2.40	1.40	0.22	0.00
Propionic	3.00	2.70	1.80	1.40	2.40	2.60	1.20	0.48
Acetic	18.4	12.7	7.30	6.30	19.1	13.8	3.70	1.30
L-Lactic	1.83	0.61	0.44	0.35	1.10	0.52	0.52	0.35
Formic	0.62	0.07	0.00	0.00	1.60	0.21	0.07	0.00
$\sum \mathrm{VFA}_{\mathrm{isot}}$	27.8	18.1	10.4	8.60	27.0	18.8	5.80	2.20
$\sum \mathrm{VFA}_{\mathrm{tit}}$		–			30.8	22.0	7.80	4.20

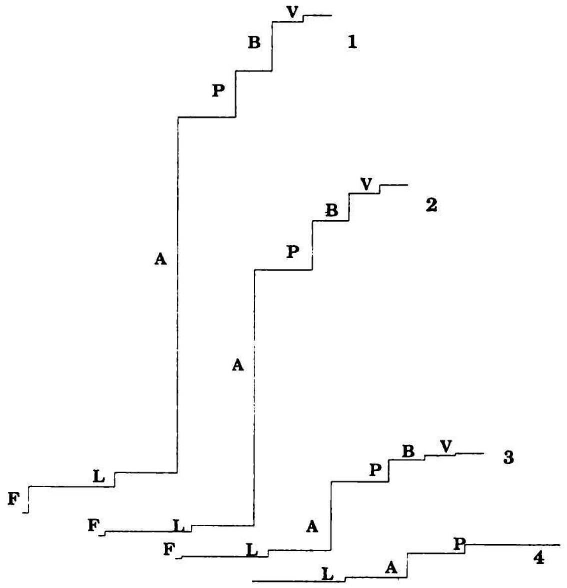

Fig. 6. Isotachophoregrams for VFA concentrations in the reactor compartments 1—4 for measurement II: F – formate, L – L-lactate, A – acetate, P – propionate, B – butyrate, V – valerate.

method measurements that gave us information about the VFA summary concentrations expressed as acetic acid showed an intensive VFA raise mainly in the first compartment after each step increase of B_v. The comparison of COD – VFA in individual compartments and in the reactor effluent with the measured values of COD revealed the fact that almost the whole COD is formed by VFA. The measurements results of the VFA concentrations by isotachophoresis are shown in Table 3. Measurement I was carried out about a week after the step change from B_v approximately 1 kg $\mathrm{m^{-3}\ d^{-1}}$ to 1.6 kg $\mathrm{m^{-3}\ d^{-1}}$, measurement II was accomplished about two weeks after step change. The VFA summary concentrations in Table 3 show that the steady state was indicated mainly by the VFA concentration decrease in the third and fourth compartments. From Table 3 it is clear that acetic acid is a prevailing acid in individual compartments whereas the number of the acids present along the reactor is being reduced. It testifies to the fact that both acidogenic and acetogenic groups of microorganisms act well. This situation is illustrated also in Fig. 6 which expresses isotachophoregrams for individual sections of the reactor. Fig. 6 includes four separated isotachophoregrams. The sections on the x axis correspond to the kind of VFA and the sections on the y axis correspond to their amount. In Table 3 summarized VFA concentrations obtained by the titration method are introduced for comparison with the total VFA concentrations measured by isotachophoresis. The comparison testifies to higher concentrations determined by titration, anyway, the method accuracy is satisfactory for judging qualitative changes in the individual ABR compartments. The calculated COD concentrations corresponding to the COD equivalents of individual VFA are presented in Table 4. The COD equivalents for VFA identified in the system are introduced in Table 5. The calculated summary values of COD are compared with the measured COD in all the compartments of the ABR in Table 4. The fraction of acidification shown in Table 4 was calculated according to the formula

$$\text{Fraction of acidified COD} = \frac{\text{COD of VFA}}{\text{Filtered COD}}\ 100\ \%$$

From Table 4 it is evident that the acidification degree in individual compartments is very high, which may cause troubles in the methanogenic phase.

Lettinga and *Hulshoff Pol* [15] claim that a complete preacidification may cause the following problems:

– Growth of excess granular sludge proceeds slowly.

– Dispersed acidogenic sludge present in the effluent of the acidogenic reactor can affect quite negatively the residence of viable granular or nongranular methanogenic sludge in the methanogenic reactor and consequently the operation of this reactor.

Table 4. Theoretical COD—VFA and COD Measured in Individual ABR Compartments 1—4

Acid	$\rho/(\text{mg dm}^{-3})$							
	Measurement I				Measurement II			
	1	2	3	4	1	2	3	4
Valeric	86.5	64.7	43.2	32.4	64.9	75.7	21.6	0.0
Butyric	560.0	280.0	113.8	61.3	385.0	218.8	35.0	0.0
Propionic	338.8	300.0	196.0	157.1	273.7	286.9	131.2	53.3
Acetic	1179.3	814.5	464.9	404.1	1224.9	882.9	236.9	84.9
L-Lactic	176.4	58.8	42.0	33.6	109.2	50.4	50.4	33.6
Formic	10.1	1.2	0.0	0.0	25.6	3.4	1.2	0.0
$\sum$COD—VFA	2351.1	1519.2	859.9	688.5	2083.3	1518.1	476.3	171.8
COD_{meas}	3200.0	1930.0	912.0	710.0	2556.0	1738.0	502.0	178.0
Fraction of acidification/%	73.5	78.7	94.3	97.0	81.5	87.3	94.9	96.5

Table 5. COD Equivalent for VFA

VFA	$m(\text{COD equivalent})/m(\text{VFA})$
Formic	0.35
L-Lactic	1.066
Acetic	1.066
Propionic	1.512
Butyric	1.816
Valeric	2.036

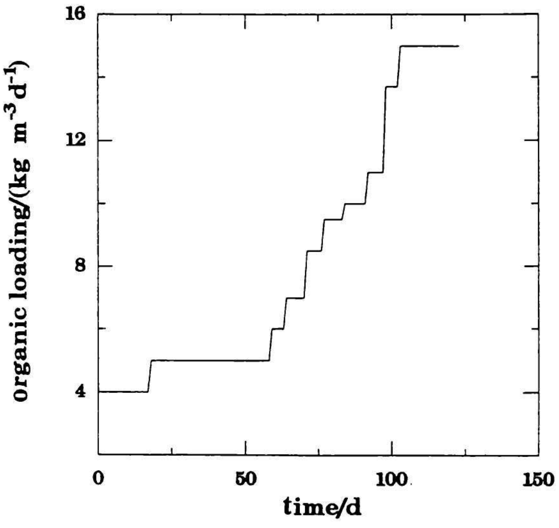

Fig. 7. Organic loading course in ABR during the second start-up. (Influent COD concentration constant; 6000 mg dm^{-3}).

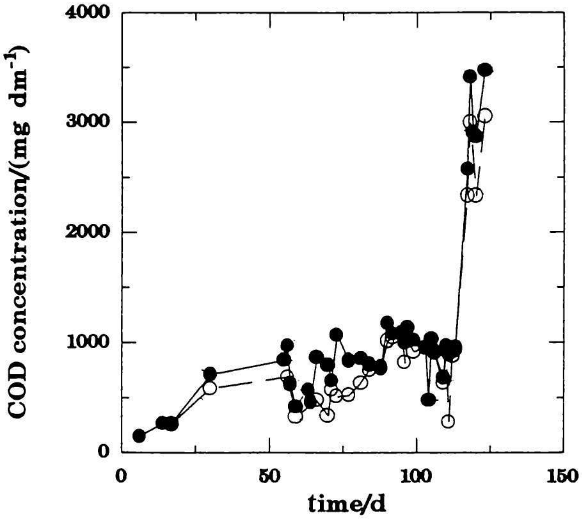

Fig. 8. Concentration of COD in the effluent from ABR for the 2nd start-up.

For this reason preacidification is recommended only to the extent of 20—40 %.

Second Start-Up of ABR

The laboratory ABR was started second time after a two-month interruption with granular sludge cultivated up during the first start-up. The same substrate was used as that introduced in the experiment with the total COD of 6000 mg dm^{-3} As the methanogenic activity of the granular sludge at the end of the first start-up was satisfactory (VFA did not accumulate in the reactor), we tried the second start-up without introducing recirculation. In the course of the next reactor performance it was confirmed that during the second start-up the reactor worked successfully even without recirculation. The course of the gradual ABR loading is expressed in Fig. 7. In the presence of the granular sludge it was easily possible to start with the organic loading of 4 kg m^{-3} d^{-1} whereas the removal efficiency was over 90 %. The course of the COD concentration in the effluent of the ABR is shown in Fig. 8, and the COD removal efficiencies reached are presented in Fig. 9. As seen in Figs. 8 and 9, the next load increasing did not substantially influence the exit COD values or the efficiency of its removal. The max-

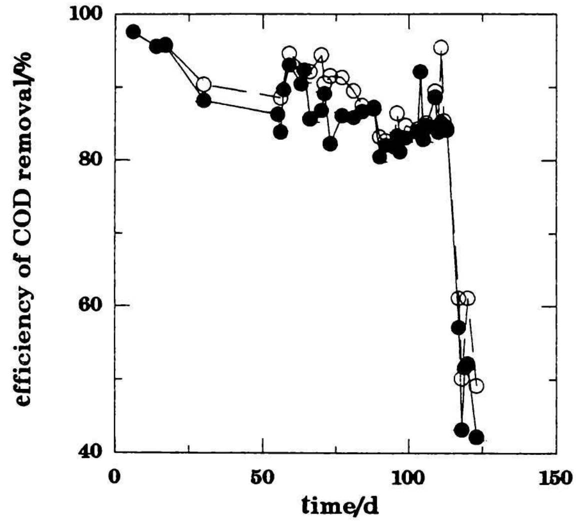

Fig. 9. Efficiency of COD removal at the 2nd start-up, filtered (○) and unfiltered (●) effluent.

imum loading reached was 15 kg m^{-3} d^{-1} with efficiencies over 80 %. The hydraulic residence time at this load was about 18 h. In the course of observation of the ABR activity also the concentrations of both filtered and unfiltered COD were measured in all four compartments of the reactor. The VFA concentrations were measured in the same way. A comparison of both the filtered and unfiltered COD concentrations showed that there were only small differences observed in individual compartments, which proves a low biomass wash-out from fully granulated beds. A bigger difference in both filtered and unfiltered COD concentrations in the first compartment was caused by a considerably acidifying environment as well as by a high ratio of acidogenic bacteria that are characteristic of a dispersion growth. The presence of a fully granulated biomass in sludge beds prevents its wash-out from the reactor and allows to reach a high hydraulic load without bigger problems.

The COD measurements during the first start-up manifested the fact that at lower loads and thus at lower residence times acidification goes on mainly in the first compartment. That is why the VFA concentrations were the highest in the first compartment and were decreasing towards the reactor effluent. The same VFA concentration courses were also gained during the second start-up at loads up to 7 kg m^{-3} d^{-1}. At loads over 8 kg m^{-3} d^{-1} the residence time in the first section was not sufficient for a full acidification and the rate of the next VFA formation in the second compartment was higher than their consumption. Thus at loads over 8 kg m^{-3} d^{-1} the VFA concentration was the highest in the second compartment. The ABR construction itself brings about spatial segregation of the basic phases of anaerobic processes (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). Hydrolysis, acidogenesis, and acetogenesis take place in the first reactor compartments. The VFA consumption and methanogenesis are often (especially at higher loading) lower than the VFA influx from the first reactor compartments. This may bring about a gradual pH decrease in the reactor and a collapse of the process of anaerobic wastewater treatment.

A high methanogenic activity as well as high volume load values (15 kg m^{-3} d^{-1}) were achieved through dosing a considerable amount of the buffer medium – $NaHCO_3$. Its dose was 1 g to 1 g of the COD influxed. At a load of 15 kg m^{-3} d^{-1} it was assumed that the sludge methanogenic activity would already be high enough to prevent VFA accumulation in the reactor. The above-mentioned $NaHCO_3$ dose is relatively high, practically unfavourable and considerably increasing salinity. Consequently, the influence of lowering the $NaHCO_3$ dose by half (0.5 g of $NaHCO_3$ to 1 g of the COD influxed) was tested on about the 110th day from the second ABR start-up. The reactor response to lowering the buffer medium dose is evident from Figs. 8 and 9. Within a week course the removal efficiency of COD went down below 50 %, the COD concentration in the effluent increased to 3000 mg dm^{-3} and the biogas production also decreased correspondingly. Even a week after redosing the original $NaHCO_3$ amount the ABR did not reach the original efficiencies of the COD removal.

The granular biomass was cultivated up in all the four ABR compartments. The granules were of a lumpy shape, grey-white to black in colour. The largest granules were in the first compartment and their size was decreasing towards the last compartment. The sludge bed in the first compartment was formed by the biomass in the granulated and suspended form whereas the suspended biomass prevailed. In this compartment there was a large amount of dispersed biomass in the water portion over the sludge bed (as already stated above when comparing the filtered and unfiltered COD). The sludge beds in the rest of the compartments were constituted only by the granular biomass.

To determine the specific methanogenic activity the same substrate was used as that in the ABR performance. The initial COD concentration in methanization tests was about 1200 mg dm^{-3} and concentration of anaerobic biomass in tests was 15 g dm^{-3} up to 20 g dm^{-3} The sludge concentration in individual compartments and its VSS contents are introduced in Table 6. Also the measured maximum specific methanogenic activities ($m(\text{COD of CH}_4)$ $(m(\text{VSS})^{-1}$ $t^{-1})$) are presented there. It is evident from papers [2, 3] that the sludge methanogenic activity decreased from the first to the last compartment. In our reactor, the maximum methanogenic activity was measured in the 3rd and 4th compartments. We assume that by us measured methanogenic activity in the first and second compartment was strongly influenced mainly by acidifying environment. This difference is evidently

Table 6. Test Results of Maximum Specific Methanogenic Activity with Granular Sludge from ABR

Compartment	Sludge concentration g dm^{-3}	Volatile suspended solids %	Maximum methanogenic activity mg g^{-1} d^{-1}
1	9.33	79.0	890
2	26.02	81.6	794
3	18.09	79.2	1135
4	27.49	78.7	911

caused by another type of the substrate used. In the mentioned papers peptone or peptone and sucrose were used as a substrate.

CONCLUSION

The granulation process in an ABR is much more sensitive in case of acidified wastewater if compared with the granulation in other types of high-rate anaerobic reactors with a sludge bed, *e.g.* in a UASB reactor or in an anaerobic hybrid reactor (AHR). In the UASB reactor and in the AHR all four phases of anaerobic processes (hydrolysis, acidogenesis, acetogenesis, methanogenesis) proceed more or less simultaneously. Mixing with biogas prevents VFA accumulation at the bottom of the reactor and acetic acid being formed is immediately at the disposal of acetotrophic methanogenic microorganisms. A cascade arrangement in an ABR is ideal for the phases segregation of anaerobic processes. It allows the VFA accumulation in the first compartments and it can lead to a situation when the rate of the acetic acid influx into the next reactor compartments will be higher than the rate of its conversion into methane. This brings about the decreasing of the pH values in the over-all baffled reactor whereas at pH under 6.5 the methanogenic process is strongly inhibited. This phenomenon was observed several times during the ABR performance. If this situation occurs, it is necessary to adjust the pH by an emergency addition of the proper base, preferably $NaHCO_3$. The highest acquired organic loading was 15 kg m^{-3} d^{-1}, yet the reactor performance with higher doses of $NaHCO_3$ can allow higher loads. The ABR can be considered to be a perspective type of reactor. The following thing, for example, is interesting about this type of reactor: the load by generated biogas is distributed through dividing the sludge bed into a number of parts. A similar principle is used *e.g.* in UASB multistage reactors. A wide application of the ABR can mostly be seen in treating nonacidified wastewater, where a two-stage anaerobic treatment (the first stage – acidification, the second stage – methanization) is recommendable.

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