Polish J. of Environ. Stud. Vol. 18, No. 6 (2009), 1051-1057

Original Research

Treatment of Septic Tank Effluent in Moving Bed Biological Reactors with Intermittent Aeration

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Received: 3 November 2008
Accepted: 2 June 2009

Abstract

Results of carbon and nitrogen removal by moving bed biological reactors operating in two modes – continuous flow and sequencing batch – are presented. Three hybrid reactors with intermittent aeration were simultaneously operated in laboratory. Real septic tank effluent from a household was treated. The research confirmed satisfactory removal of carbon and nitrogen (up to 88% and 64%, respectively) by the hybrid reactors. The most preferable conditions for carbon and nitrogen removal were: hydraulic retention time = 0.55 d with 15/15 minutes aeration/non-aeration intervals in continuous flow reactors and four-hour cycles in sequencing batch reactors. Higher COD loadings on reactors' volumes induced higher biomasses of biofilm and lower concentrations of activated sludge, but sludge wastage was negligible. Various groups of organisms were observed in both – activated sludge flocks and biofilm. The highest concentration of filamentous microorganisms was observed in the reactor with the highest COD loading. Rotifers were much more abundant in biofilm than in flocks, due to their relatively long growth time.

Keywords: activated sludge, biofilm, septic tank effluent, MBBR, nitrogen, continuous flow, SBR

Introduction

Two technologies are commonly used for biological treatment of sewage: activated sludge and trickling filters. A moving bed biological reactor (MBBR) is a compilation of these two technologies. The biomass in the MBBR exists in two forms: suspended flocks and a biofilm attached to carriers. It can be operated at high organic loads and it is less sensitive to hydraulic overloadings. MBBRs are used to treat sewage with high carbon and nitrogen compound concentrations. Moving carriers can be used to retrofit overloaded wastewater treatment plants. Such hybrid reactors work with a continuous flow or sequencing batch [1, 2].

Complex processes of carbon oxidation, nitritation, nitratation and denitrification may take place in one reactor. Due to specific conditions, important for microorganisms, e.g. intermittent aeration [3], it is possible to carry out simultaneously nitrification/denitrification processes or one of the recently discovered processes: ANAMMOX, SHARON or CANNON [4]. These processes seem to be more relevant for ammonia removal from sewage lacking organic matter than the conventional nitrification/denitrification process. As a rule, the C/N ratio in septic tank effluent is relatively low (1 < C/N < 6), thus biological nitrogen removal is limited.

The aim of this study was to assess removal efficiency of hybrid reactors with intermittent aeration under various organic and hydraulic loadings and to determine organic and nitrogen compounds' utilization rates.

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Experimental Procedures

The experiment was carried out in the lab at the Section of Rural Water Supply and Sanitation of August Cieszkowski Agricultural University of Poznań.

Three simultaneously operating hybrid reactors with continuous flow (CFRs) and next sequencing batch (SBRs) were used. The biomass in the reactors existed in two forms: as activated sludge (flocks) and as biofilm on the moving-bed carriers. The experimental set-up is shown in Fig. 1.

The moving bed consisted of 2,000 corrugated cylindrical carriers, made of polypropylene, of diameter 13 mm and height 13 mm. The specific surface of the moving bed was equal to 583±5 m^2/m^3. The number of moving bed carriers was calculated with respect to reactor load by organic compounds, as earlier described by Makowska [5]. The sewage, originated from one family household, was preliminary treated in a septic tank. The septic tank effluent was pumped to a storage tank and then it supplied continuously to reactors using a peristaltic pump. The hydraulic loadings of CFRs were equal to Q, $2Q$ and $4Q$, where Q is a flow rate for HRT = 1.11 to 1.31 d. Sludge recirculation from the secondary settler was equal to 50%. The reactors were aerated intermittently by a coarse-bubble diffuser, installed at the bottom of each reactor. The periods of aeration and non-aeration were equal for all three CFRs and were the specific parameters in each of four research periods. The most efficient aeration/non-aeration interval for CFRs was chosen for SBRs as optimal. The cycle duration of SBR operating was equal to: 6 hours in period 1, 4 hours in period 2 and 3 hours in period 3. It consisted of the following phases: filling (315 min in period 1, 195 min in period 2 and 135 min in period 3), intermittent aeration (15/15 min), sedimentation and decantation (the last 45 minutes of the cycle). Its hydraulic retention time (HRT_{SBR}) was calculated using equation:

$$HRT_{SBR} = t_c \frac{V_d + V_p}{V_d} - \frac{t_f}{2} \qquad (1)$$

...where: t_c – cycle duration, d,

V_d – sewage dosage volume, dm^3,

V_p – passive part of reactor volume, dm^3,

t_f – filling time, d,

Each research period lasted 2 months. Sewage temperature ranged from 17 to 22ºC. Start-up period for CFRs lasted 4 weeks. Biomass on carriers remained in the reactors without removing it between research periods. The technological parameters of the reactors are shown in Table 1.

The following variables were measured in filtered samples: COD (photometric method) and BOD (respirometric method) in the inlet and outlet sewage, concentration of nitrogen compounds (photometric method) and total Kjeldahl nitrogen concentration (distillation method). Concentration of activated sludge organic matter, i.e. volatile suspended solids, (direct gravimetric method) and mass of organic matter in the biofilm (indirect - via total Kjeldahl nitrogen concentration) were determined in each reactor once per week. Measurements of dissolved oxygen (DO) concentration in the reactors were carried-out in time intervals equal to 1 minute. DO concentrations during aeration ranged between 0.3 and 0.8 mg/dm^3, except for the first period in SBRs, for which it varied from 1.0 to 3.0 mg/dm^3. Concentration of protons (pH) and sewage temperature were also observed.

On the base of obtained results the following characteristics were calculated:

- specific carbon and nitrogen utilization rates [6]:

$$q = \frac{Q \cdot (S_0 - S_e)}{V \cdot X} \qquad (2)$$

...where: Q – sewage flow, dm^3/d,

S_0 - concentration of pollutant at the inlet, g/dm^3,

S_e - concentration of pollutant at the outlet, g/dm^3,

V - volume of reactor, dm^3,

X - biomass concentration in the reactor, $gVSS/dm^3$.

- removal efficiencies:

$$\eta = \frac{S_0 - S_e}{S_0} \cdot 100\% \qquad (3)$$

...where: notation as in Eq. (2).

Biological examinations of activated sludge and biofilm were made every week using standard methods. They included macroscopic investigations (colour and smell) and microscopic investigation of sludge flock morphology (structure, shape and volume) as well as biological characteristics of activated sludge and biofilm, using 100 x and 400 x magnification [7]. The results of the biological assessment are presented as population density classes (Table 2), as an average of two replications.

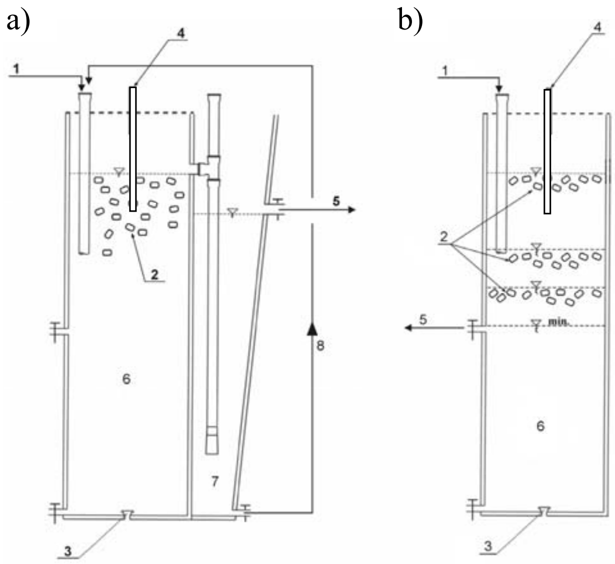

Fig. 1. Experimental set-up. a) CFR, b) SBR;
1 – inlet of septic tank effluent, 2 - moving carriers, 3 – air diffuser, 4 – oxygen measurement port, 5 – outlet of treated sewage, 6 – reactor, 7 – secondary clarifier, 8 – recirculation.

Table 1. Mean values of technological parameters.

Continuous-flow reactors – STAGE I												
Research period	Period 1			Period 2			Period 3			Period 4		
Reactor number	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
Reactor volume, V, dm^3	75			75			75			75		
Flow. Q. dm^3/d	58.4	114.9	294.9	62.1	118.8	214.3	72.4	142.2	259.5	67.8	137.4	224.2
Retention time, HRT, d	1.30	0.66	0.26	1.31	0.69	0.36	1.11	0.54	0.30	1.11	0.55	0.34
Organic load, A, g COD /(g VSSd)	0.11	0.25	1.23	0.10	0.54	1.65	0.11	0.28	1.36	0.17	0.94	2.56
Activated sludge mass in the reactor, g VSS	79.18	74.18	33.92	128.1	46.53	17.67	116.5	88.48	24.81	104.1	28.90	7.78
Biofilm mass in the reactor, g VSS	14.44	11.58	22.49	4.78	7.96	13.53	3.31	5.47	9.92	3.34	6.62	11.92
Aeration/non- aeration intervals, min/min	75/45			45/45			30/30			15/15		
S_0 (COD), g COD/m^3	169 ± 14			209 ± 6			174 ± 8			214 ± 8		
S_0 (BOD_5), g BOD_5/m^3	132 ± 8			137 ± 5			106 ± 10			131 ± 5		
S_0 (N_{tot-K}), g N/m^3	53.5 ± 3.6			51.7 ± 1.6			41.8 ± 3.0			46.7 ± 2.2		

Sequencing batch reactors – STAGE II									
Research period	Period 1			Period 2			Period 3		
Reactor	R1	R2	R3	R1	R2	R3	R1	R2	R3
Passive volume, Vp, dm^3	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Flow, Q, dm^3/d	44.3	92.7	159.5	69.1	117.6	198.5	97.4	171.7	272.2
Sewage dosage volume, Vd, dm^3	11.08	23.18	39.88	11.52	19.60	33.08	12.18	21.46	34.03
Retention time, HRTSBR, d	1.05	0.58	0.40	0.70	0.44	0.31	0.50	0.32	0.23
Cycle duration, h	6			4			3		
Organic load, A, g COD /(g VSSd)	0.02	0.04	0.17	0.08	0.21	0.53	0.45	0.78	1.19
Activated sludge mass in the reactor, gVSS	199.3	226.9	123.9	106.1	62.86	50.81	25.53	27.15	33.11
Biofilm mass in the reactor, g VSS	1.11	1.30	2.09	2.53	2.86	7.96	4.37	7.84	8.36
Aeration/no aeration intervals, min/min	15/15			15/15			15/15		
S_0 (COD), g O_2/m^3	166 ± 11			169 ± 9			185 ± 18		
S_0 (BOD_5), g O_2/m^3	80 ± 4			101 ± 7			136 ± 10		
S_0 (N_{tot-K}), g N/m^3	42.5 ± 2.0			39.0 ± 1.8			40.3 ± 2.7		

Results and Discussion

Carbon Compounds

The best quality of the treated sewage concerning BOD_5 and COD was provided by the CFRs R1 and R2. Shorter aeration and non-aeration time intervals brought about higher pollutant utilization rates. The lowest BOD_5 in the outflow from CFRs was obtained in reactors R1 (5.1-8.6 g/m^3). Reactor R3 gave much higher BOD_5 in its effluent (21.3-29.0 g/m^3) because of its high loading.

In the SBRs the best quality of treated sewage (BOD_5 and COD) was obtained in period 2 (4-hour cycle, 15/15 min aeration/non-aeration intervals). In all series the best quality was provided by reactor R1 (at the lowest loading), for which BOD_5 in the final effluent ranged from 5.7 g/m^3 to 29.0 g/m^3.

Carbon compounds utilization rates correlated with their concentrations in the final effluent (Fig. 2). In SBRs the lesser organic loading and shorter operation cycles' time, the higher organic compounds utilization rate. These results were related to a decrease in biomass within reactors [8].

Table 2. Population density classes.

Class	Filamentous organisms	Single bacteria	*Zoogloea sp.* *Spirillum sp.* *Spirochaeta sp.*	Protozoa	Metazoa
0	Not observed	Not observed	Not observed	Not observed	Not observed
1	1-4 filaments in the slide	Single organisms in the field of view	Occasionally in the slide	1-10 organisms in the slide	1-5 organisms in the slide
2	5-10 filaments in the slide	Numerous organisms in the field of view	5-10 organisms in the slide	1-10 organisms in the field of view	5-10 organisms in the slide
3	10-20 filaments in the slide	Numerous organisms in the field of view	Over 10 organisms in the slide	Over 10 organisms in the field of view	Over 10 organisms in the slide
4	Over 20 filaments in the slide	-	-	-	-
5	Very high number	-	-	-	-

Removal efficiencies decreased with increasing organic loads as shown in Figs. 3 and 4. Carbon removal efficiency reached 88% in CFR and 86% in SBR, both in the lightly loaded reactors R1. It was comparable with those in other studies, e.g. 87-96% [9] or 75-85% [10]. The shorter aeration and non-aeration time intervals, the better BOD and COD removal (except for the fourth period). Reactor R3, as the most heavily loaded, had the lowest efficiency.

Nitrogen Compounds

Nitrogen removal efficiency was lower than carbon removal efficiency (Fig. 3). In SBRs, the lowest concentration of nitrogen compounds in the outflow was obtained during the 2nd period. The highest nitrogen removal efficiency in all periods was provided by reactor R1 (best results in period 1). It was observed that the higher the organic load, the lower the ammonium and total nitrogen removal efficiency (Figs. 3 and 4).

Nitrogen compound utilization rates rose when aeration time intervals became shorter. Nitrogen compound removal in the third reactor was similar to carbon removal – high q values corresponded to low efficiency values, therefore, as the most effective reactor R2 was recognized.

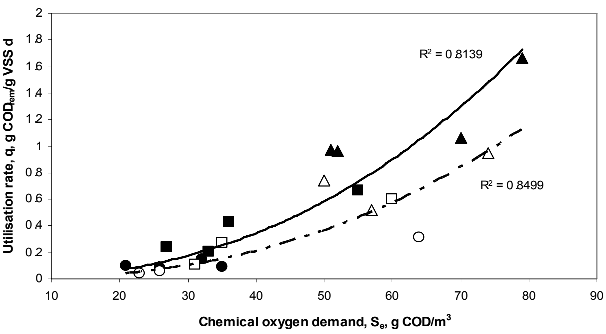

Fig. 2. Organic carbon utilization rates as functions of COD in the final effluent (solid symbols and line – CFR, empty symbols and dashed line – SBR; circles – R1, squares – R2, triangles – R3).

The highest nitrogen compound utilization rate in an SBR was observed in the 3rd period. It was related to a lower biomass concentration than in previous periods – but not correlated with compound removal efficiency [8]. The highest values of compound utilization rate were provided by reactor R1 in all periods.

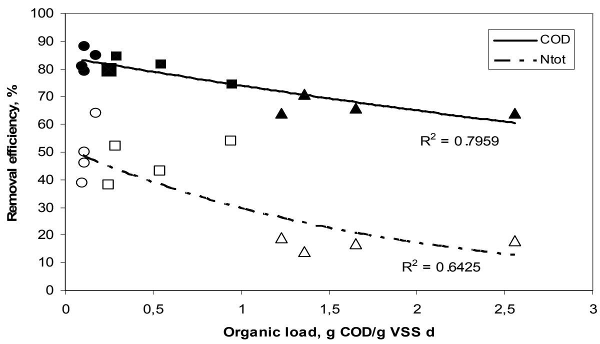

Fig. 3. Organic carbon and total nitrogen removal efficiencies in CFRs as functions of organic load (circles – R1, squares – R2, triangles – R3).

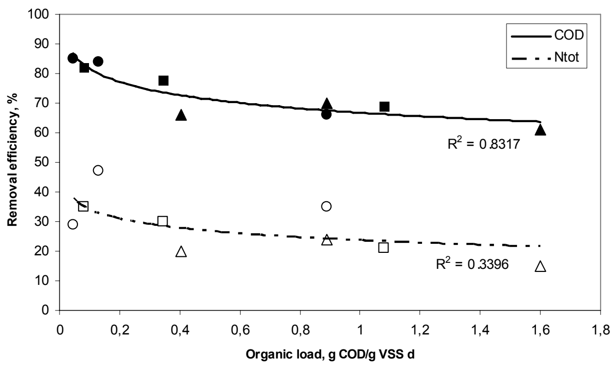

Fig. 4. Organic carbon and total nitrogen removal efficiency in SBRs as a function of organic load (circles – R1, squares – R2, triangles – R3).

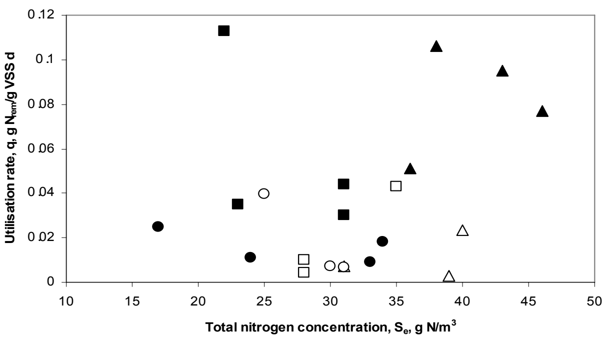

Fig. 5. Total nitrogen utilization rates versus its concentration in the final effluent (solid symbols – CFR, empty symbols – SBR) (circles – R1, squares – R2, triangles – R3).

Moderate average efficiencies of nitrogen removal were obtained in both CFRs and SBRs - correspondingly up to 64% and 46%. A similar effect of nitrogen compound removal was obtained by Tomaszek and Grabas: 48-95% [9], and higher – 70-95% by Paul et al. [10].

The influence of organic compounds' loadings on nitrogen compounds concentration in outflow sewage was statistically confirmed. However, total nitrogen utilization rates were not correlated with its concentrations in the final effluent (Fig. 5). An analysis of variance showed that differences between pollutant removal efficiencies, for reactors running at different loadings, were statistically significant for both CFRs and SBRs (calculated F > critical F for $\alpha = 0.05$). An impact of aeration interval duration and impact of HRT on nitrogen compound removal efficiency in CFRs were observed. Similarly, the cycle duration significantly influenced carbon and nitrogen compound removal efficiency in SBRs.

Other significant factors influencing nitrogen removal, according to the literature [11, 12] are: dissolved oxygen concentration and aeration to non-aeration time ratio. Low C/N allows for simultaneous nitritation/denitrification processes [13, 14]. At a poor access to organic compounds, the denitrifying microorganisms can also use the endogenic carbon source [15]. However, this study did not show any significant influence of the C/N ratio on nitrogen removal efficiency for both CFRs (0.8 < C/N < 1.8) and SBRs (1.5 < C/N < 1.9).

Sludge Production and Waste

Sludge production was relatively low due to the low input of total suspended solids from the septic tank (on average 49 mg/dm³), the probable inhibitory action of H_2S contained in putrified effluent from the septic tank, as well as low C/N ratios.

The highest sludge concentration (not including the biofilm) in the CFRs was 1.7 g/dm³ and the lowest (at the highest loadings) was equal to 0.1 g/dm³. In the last case, the total biomass (including biofilm) weighed 0.26 g/dm³, which was still very low compared to typical sludge concentrations in activated sludge tanks (2-5 g/dm³). In such conditions, there was no wastage of an excess sludge, except for the total suspended solids in the final effluent and the sewage samples. Nevertheless, the maximum TSS concentration in the final effluent did not exceed 50 mg/dm³, the upper limit for small treatment plants in Poland.

Microorganisms

The size of activated sludge flocks had varied, having their average diameter in the range 150-500 μm in all reactors. In both types of reactors the biofilm on the moving bed carriers was poorly developed. It did not cover the whole surface of carriers, but existed as separate small colonies (mushroom shape). The inner surface of carriers was only locally colonised by small colonies of stalked ciliates (Fig. 6).

Various groups of organisms, during the whole research time, were observed in both – activated sludge flocks and biofilm, namely free-swimming ciliates, creeping ciliates, stalked ciliates, rotifers, filamentous microorganisms, nematodes and others. The number of groups of microorganisms varied over time. The most common genera of ciliates in both activated sludge and biofilm was *Epistylis* and *Vorticella*. Nematodes were observed occasionally.

Some differences between the number of organisms in activated sludge and in the biofilm were observed. During almost the whole time of experiments, the observed number of rotifers in activated sludge flocks in all reactors was very small, but it was much higher in the biofilm, especially in period 3 in SBRs. The significance difference between the means for biofilm and flocks was estimated using t-Student statistics; t calculated equalled 2.83 (critical value = 2.78 for $\alpha = 0.05$, for the number of replications equal to 5, $df = 4$). It was related to the long growth time of these organisms [16].

It was observed that the concentration of filamentous microorganisms in both CFRs and SBRs was the highest in reactor R3 (as shown in Fig. 7), which had the highest COD loading. A significant statistical difference between the mean for reactor R3 and the mean for reactor R1, was found in SBRs, using t-Student statistics; $t = 8.98$ ($t_{er} = 2.2$, for $\alpha = 0.05$, for the number of replication equalled 13, $df = 11$).

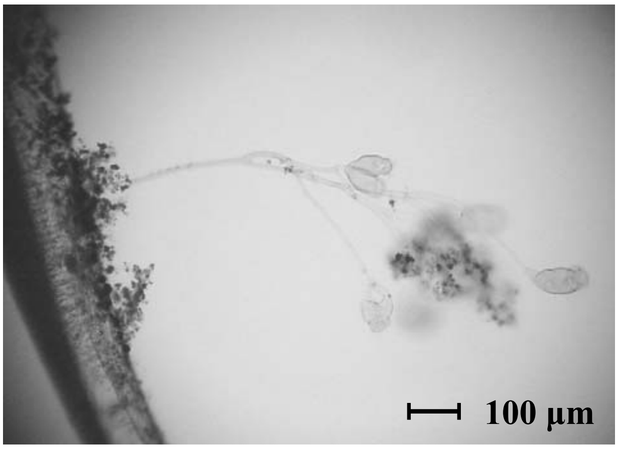

Fig. 6. The inner surface of a carrier covered by a small colony of stalked ciliates.

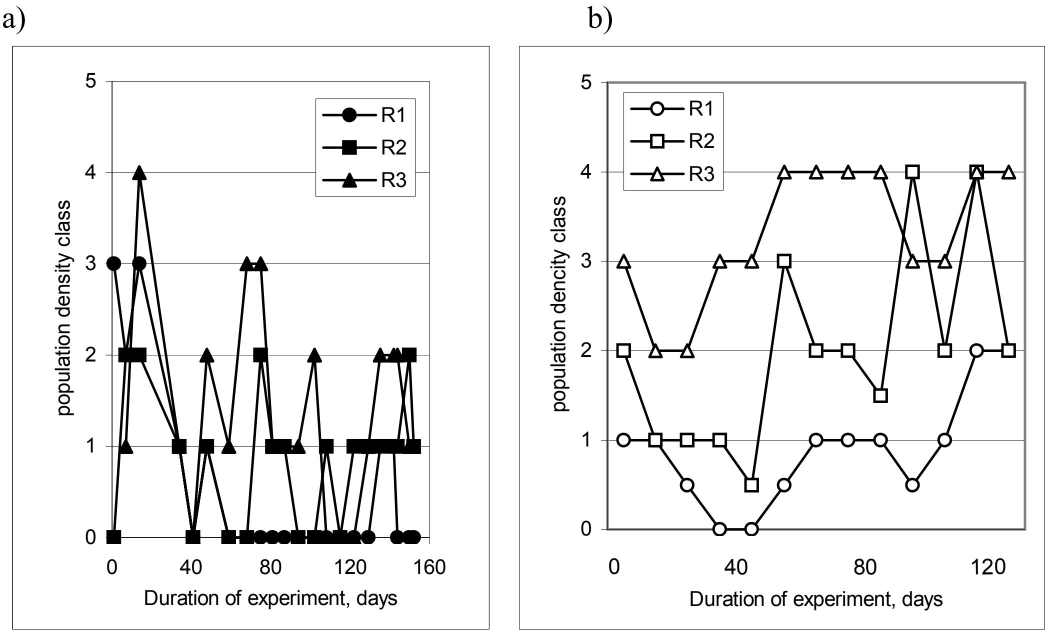

Fig. 7. Number of filamentous microorganisms in the activated sludge: a) CFRs, b) SBRs

The observed number of filamentous microorganisms in CFRs was often higher in flocks than in biofilm, especially in reactor R3. The number of filamentous organisms in SBRs had been increasing, with the increase in organic loading. In the SBR R2 filamentous organisms (Fig. 8) were dominant during period 2 and period 3.

A relatively high number of stalked ciliates was observed in both stages, both in flocks and in biofilm. Domination of this form of ciliata often corresponds to good pollutant removal efficiency [6].

Conclusions

1. High average efficiencies of carbon removal and moderate efficiencies of nitrogen removal from septic tank effluent in the investigated hybrid reactors were obtained, correspondingly 60 to 88% and 14 to 64%.

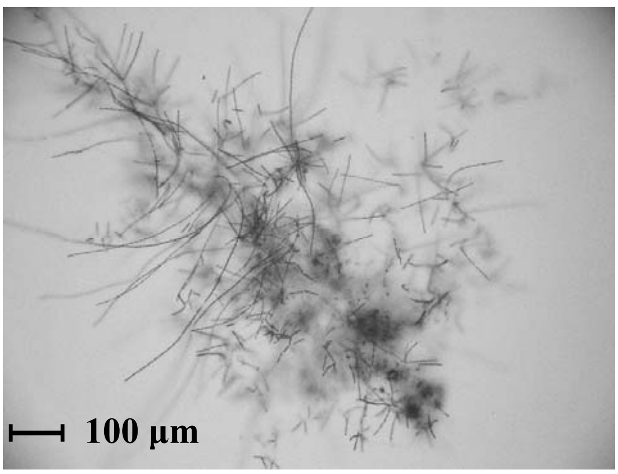

Fig. 8. Dominating filamentous organisms in reactor R2 during stage II.

At organic loads lower than 1 g COD/gVSSd, the total nitrogen removal was significantly higher in CFRs (38-64%) than in SBRs (19-48%).
2. The most preferable conditions for carbon and nitrogen removal in CFRs were 13 hours retention time and 15/15 minutes aeration/non-aeration intervals, and in SBRs a four-hour cycle in the same aeration regime.
3. Nitrogen removal was possible due to nitrification/denitrification processes running simultaneously during the intermittent aeration. Shorter aeration cycles brought about relatively longer anoxic conditions, favourable for denitrifying bacteria.
4. The efficiencies of carbon and nitrogen removal decreased with an increase in organic loading.
5. Average utilization rates of organic and nitrogen compounds in both types of reactors were higher for the greater organic loadings.
6. Various groups of organisms were observed in both activated sludge flocks and biofilm during all research time, their numbers were varying in time; concentrations of filamentous microorganisms were the highest in reactors with the highest COD loadings; rotifers were fewer in flocks than in biofilm due to their relatively long growth time.
7. Higher COD loadings on both CFRs and SBRs brought about higher biomasses of biofilm and lower concentrations of activated sludge, but the excess sludge wastage in both stages was negligible.

Acknowledgements

The authors gratefully acknowledge the funding of this investigation by the Polish State Committee for Scientific Research (grant No. 3 PO6S 07323).

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