ARCHIVES OF ENVIRONMENTAL PROTECTION
vol. 36 no. 3 pp. 15 - 25 2010
PL ISSN 0324-8461

BIOMASS YIELD IN POROUS CERAMIC CARRIERS FOR MUNICIPAL WASTEWATER TREATMENT

MAGDALENA ZIELIŃSKA*, IRENA WOJNOWSKA-BARYŁA

University of Warmia and Mazury in Olsztyn, Department of Environmental Biotechnology
Słoneczna str. 45G, 10-709 Olsztyn, Poland
* Corresponding author e-mail: magdalena.zielinska@uwm.edu.pl

Keywords: Immobilization of activated sludge, wastewater treatment, biomass yield.

Abstract: Two different porous ceramic carriers with immobilized activated sludge comprised a stationary filling of the reactors. Municipal wastewater was treated at hydraulic retention times from 15 to 70 min and internal circulation capacity of 20, 40 and 60 $dm^3 \cdot h^{-1}$. Depending on hydraulic retention time, the sludge yield ranged from 0.138 to 0.066 g $TSS \cdot g\ COD^{-1}$ in reactor I and from 0.175 to 0.107 g $TSS \cdot g\ COD^{-1}$ in reactor II. An increase in volumetric loading rate and internal circulation capacity caused a reduction in sludge yield. A decrease in the sludge yield corresponded to an increase in the ratio of endogenous to substrate respiration by the immobilized biomass.

INTRODUCTION

In aerobic wastewater treatment systems, large amounts of excess sewage sludge are formed, and their treatment and disposal involves significant investment and operating costs. For this reason the minimization of sludge production has become important and technological solutions to sludge reduction are therefore needed. In the case of single-stage activated sludge systems, it is known that reduced sludge yield is obtained when the plant is operated at increased solids retention time (SRT) [13]. Such a strategy requires high aeration volumes and results in increased costs. Other methods of lowering sludge yield include promotion of bacterial predation implying the elongation of food chains [27], increasing process temperature or the introduction of chemical uncoupling [22].

One method of minimizing the sludge yield is the use of reactors with immobilized biomass; these can be operated at increased sludge concentrations, resulting in reduced sludge loading rates without the need of additional aeration volume. The immobilization of activated sludge permits a high concentration of biomass in the reactor and long solids retention time (SRT) [8], which can limit sludge production [6]. According to Gander *et al.* [12] and Chiemchaisri, Yamamoto [7], the higher the biomass concentration the lower the Food/Microorganisms ratio (F/M). For this reason wastewater can be treated with reduced sludge production. For a conventional activated sludge system, F/M is in the range of 0.05–1.5 kg $BOD \cdot kg\ MLSS^{-1} \cdot d^{-1}$ [1]. For systems with a biomass concentration from 5 to 20 kg $MLSS \cdot m^{-3}$, F/M usually equals 0.1 kg $BOD \cdot kg\ MLSS^{-1} \cdot d^{-1}$. A low F/M ratio means little substrate per unit of biomass, which leads to a competition among the microorganisms and results in reduction of the net sludge production [24]. Under conditions of high biomass concentration, low F/M and long SRT, the processes of pollution removal function according to the maintenance concept. This reflects insufficient food entering the biomass to allow cell growth [16]. Based on RNA research, Witzig *et al.* [29] have indicated that bacteria present in the highly concentrated biomass of the membrane reactor used the energy supplied for their maintenance metabolism and were not in a physiological state characteristic for growth. Only if energy is supplied in excess, are bacteria able to grow.

Numerous researches on immobilization biotechnology involve mainly the exploitation of reactors with different kinds of moving carriers. However, the examination of wastewater treatment effectiveness and sludge production in stationary ceramic carriers (advantageous in terms of mechanical durability) and at different hydraulic loadings is not widespread. In this work the exploitation of bioreactors filled with static macroporous ceramic carrier with immobilized biomass was the leading objective. The impact of hydraulic retention time (HRT) and capacity of internal circulation (q) on biomass yield was investigated. The composition of wastewater also influences sludge production. For this reason the determination of the chemical characteristics of wastewater has been found to have great theoretical and practical significance. Assessment of the concentration of readily biodegradable COD is particularly important, since this parameter is the only substrate component directly related to microbial growth.

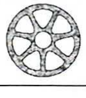
In order to determine the physiological state and metabolic activity of bacteria present in the reactor with immobilized biomass, the oxygen uptake rates in substrate (exogenous) and endogenous respiration were examined.

MATERIALS AND METHODS

Characteristics of carriers

Activated sludge was immobilized in two porous cylindrical carriers. The carriers differed in internal structure, number of internal channels, size of internal surface and total volume (Tab. 1). The carrier volume was calculated as the total volume with the volume of channels. The pore diameters of both carriers ranged from 4 to 6 μm and the material porosity was 35–40%. These characteristics were provided by the carrier producer, TAMI Industries, Germany. Both carriers were made as a structured bed from a mixture of aluminum oxide (Al_2O_3), titanium oxide (TiO_2) and zirconium oxide (ZrO_2). From this powdered mixture a paste was made and formed in the shape of multi-channeled tubes. The tubes were then sintered at > 1000°C.

Table 1. Characteristics of porous carriers

Carrier	Cross-section	External diameter [mm]	Hydraulic diameter [mm]	Internal surface [m^2]	Total volume [dm^3]	Length [mm]
I		10	3.6	0.04	0.1	1178
II		25	6.0	0.20	0.6	1178

Reactor characteristics

Each carrier with immobilized biomass comprised the stationary filling of the reactor with internal circulation. Carrier I was placed into reactor I, carrier II – into reactor II. The total volume of the reactors I and II was 0.7 dm^3 and 1.2 dm^3, respectively. In both reactors free space outside the carrier equaled to 0.6 dm^3.

The bioreactors were continuously aerated. Air was supplied at 50 $dm^3 \cdot h^{-1}$ to reactor I and 120 $dm^3 \cdot h^{-1}$ to reactor II, in order to maintain dissolved oxygen (DO) concentration in the effluent of about 2 mg $O_2 \cdot dm^{-3}$. The general reactor scheme and dimensions of reactor II (in millimeters) are shown in Figure 1.

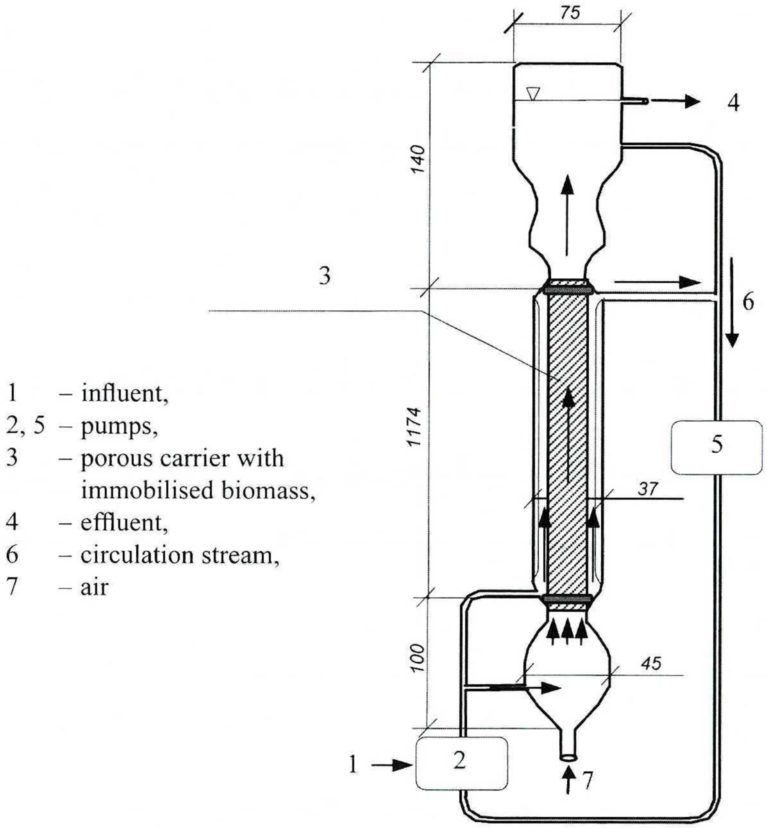


Fig. 1. Scheme of the reactor

The carrier was fixed into the bioreactor using O-rings. Two spaces were created inside the bioreactor: the internal channels and the external space. Raw wastewater flux and the circulating stream were mixed before they flowed into the reactor. The influent was divided into two streams flowing parallel through the external space and internal channels. This allowed the pressure on the internal and external surfaces to be kept equal.

Colonization procedure

Activated sludge, derived from a full scale wastewater treatment plant with nitrification, was the source of inoculum. This was thickened to a concentration of about 23 g $TSS \cdot dm^{-3}$.

Immobilization was carried out by circulating the activated sludge in the reactors for 24 h. The circulation was conducted in such a way that it allowed the biomass to flow through the internal channels of the carriers and not through the space outside the carriers. As a result, the biomass was immobilized both inside the pores and on the internal surfaces of the carriers. The initial carrier loading amounted to 24.5 g $TSS \cdot dm^{-3} \cdot d^{-1}$ (carrier I) and 18.2 g $TSS \cdot dm^{-3} \cdot d^{-1}$ (carrier II). The carrier loading was calculated from the total volume of a carrier.

Wastewater characteristics

Municipal wastewater taken each day directly from a sewer pipe inspection chamber was introduced to the reactors. Average concentration of total chemical oxygen demand (COD) was 373.6 ± 280.4 $mg \cdot dm^{-3}$, soluble COD (after filtration) 121.9 ± 47.8 $mg \cdot dm^{-3}$, Kjeldahl nitrogen 48.4 ± 14.2 $mg \cdot dm^{-3}$, ammonium nitrogen 27.8 ± 8.8 $mg \cdot dm^{-3}$ and total suspended solids 228.0 ± 212.2 $mg \cdot dm^{-3}$.

Experimental set-up

The studies were carried out for hydraulic retention times (HRT) of 70, 60 and 30 min for both reactors. Additionally, a HRT of 15 min was carried out for reactor I due to continued high efficiency of COD removal (over 90%). In Table 2 the carrier surface loading rates (SLR) and volumetric loading rates (VLR) for both reactors are shown. HRT was altered by changing the wastewater feed rate. The volumetric loading rate was calculated per total volume of the carrier according to German ATV directions concerning dimensioning of biological beds. Total carrier volumes are given in Table 1. For reactor I at a HRT of 60 min and for reactor II at a HRT of 70, 60 and 30 min, a variable internal circulation capacity (q) was used: 20, 40 and 60 $dm^3 \cdot h^{-1}$. In the remaining series, internal circulation capacity was maintained at 40 $dm^3 \cdot h^{-1}$.

Table 2. Scheme of research

Reactor		I				II		
HRT	[min]	70	60	30	15	70	60	30
SLR	[g $COD \cdot m^{-2} \cdot d^{-1}$]	15.3	18.8	48.8	114.6	15.6	16.8	47.9
VLR	[g $COD \cdot dm^{-3} \cdot d^{-1}$]	6.5	8.0	20.8	48.8	5.4	5.8	16.6

All experimental series were carried out consecutively in the same reactor. Before the start of the first experimental series inoculum was immobilized in the carriers and used throughout the whole experiment. The adaptation period before each series lasted about 30 days and was considered complete when the range of changes of particular parameters of the effluent (COD, TKN, N_{NH4}) within 7 days did not exceed 5–10%. At each hydraulic retention time, after biomass adaptation for the experimental conditions, the research was carried out for about 3 weeks. During the experiment, samples were collected twice a day. The data presented are the arithmetic mean of the experimental results.

Analytical methods

The wastewater was assayed for the concentration of organic compounds, expressed as COD and soluble COD (measured after filtration), volatile acids, Kjeldahl nitrogen, ammonium nitrogen and total suspended solids, according to Polish Standards [23].

The respirometric activity of the immobilized biomass was measured in an OxiTop device. In order to determine the substrate respiration, a sample of the biomass collected from the carriers, raw wastewater and allylthiourea as a nitrification inhibitor were put into measuring vessels. To determine the oxygen uptake for endogenous respiration, the measuring vessels included a sample of biomass (centrifuged at 4000 rpm for 3 min) and distilled water. The organic loading rate was maintained at 0.25 g COD·g $TSS^{-1}\cdot d^{-1}$ (similar to that used by van Benthum *et al.* [5]).

Calculation methods

The sludge yield (Y) was calculated with the use of equation (1). It was assumed that the total excessive biomass was washed out of the reactor and all TSS from the influent were solubilised and hence it was not included in the calculation of the sludge yield [13]:

$$Y = \frac{TSS_1 - TSS_0}{COD_i - COD_e}, \quad [\mathrm{g\,TSS \cdot g\,COD^{-1}}] \tag{1}$$

TSS_1 – total suspended solids in effluent at time t_{n+1} [mg TSS·dm^{-3}]
TSS_0 – total suspended solids in effluent at time t_n [mg TSS·dm^{-3}]
COD_i – organic compounds in influent [mg COD·dm^{-3}]
COD_e – organic compounds in effluent [mg COD·dm^{-3}]
n – day of sampling

In the composition of raw wastewater, the organic compounds expressed as COD were divided into soluble and particulate. The concentration of particulate COD was calculated as the difference between total COD and soluble COD. Particulate organic compounds were divided into biodegradable and non-biodegradable or slowly biodegradable. Soluble organic compounds included very readily biodegradable, readily biodegradable and non-biodegradable or slowly biodegradable components. The fractions of organic compounds were calculated using coefficients given by Barnard [4]. It was assumed that non-biodegradable or slowly biodegradable particulate compounds account for 5% of total COD, and non-biodegradable or slowly biodegradable soluble compounds account for 3% of total COD.

The oxygen uptake rates (r) for substrate and endogenous respiration were described by first-order kinetic and defined by the following equation (2):

$$r = k \cdot C_t \tag{2}$$

k – constant of reaction rate [h^{-1}]
C_t – concentration of oxygen used after time t [mg O_2·dm^{-3}]

The solution for this could be fitted to the experimental data according to the equation (3):

$$C_t = C_0 \cdot (1 - e^{-k \cdot t}) \tag{3}$$

C_0 – initial oxygen concentration [mg O_2·dm^{-3}]
t – time [h]

Constants of reaction rates were determined based on the experimental data by non-linear regression with the use of Statistica 7.

RESULTS AND DISCUSSION

Reactor I was operated at hydraulic retention times (HRT) from 70 to 15 min, and at volumetric loading rate (VLR) from 6.5 to 48.8 g COD·dm^{-3}·d^{-1}. In reactor II, HRT was maintained from 70 to 30 min, and VLR from 5.4 to 16.6 g COD·dm^{-3}·d^{-1}. Under these technological conditions, low values of sludge yield were obtained: for reactor I from 0.138 to 0.066 g TSS·g COD^{-1}, for reactor II from 0.175 to 0.107 g TSS·g COD^{-1} (Tab. 3). Other authors have observed similar biomass growth. Performance of a sequencing batch reactor using a membrane for effluent filtration was investigated by Choo, Stensel [8]. During operation at a 1400-day calculated SRT, the average observed biomass yield was approximately 0.03 g MLVSS·g COD^{-1} at the organic loading rate of 0.3 g COD·m^{-2}·d^{-1}. In a membrane reactor the excess sludge production was 0.094 g MLSS·g COD^{-1} at 5400 g BOD$_5$·m^{-3}·d^{-1} [17]. In a membrane bioreactor Cicek *et al.* [9] the obtained sludge production was 0.29 g TSS·g COD^{-1} at the organic loading rate of 650 g COD·m^{-2}·d^{-1}. A sludge yield of 0.2–0.3 g TSS·g COD^{-1} was noticed in the reactor with biomass immobilized on cylindrical carriers [2]. Zhan *et al.* [30] calculated the biomass yield coefficient at a level of 0.18 g VSS·g COD^{-1} in a sequencing batch biofilm reactor treating synthetic dairy wastewater at a volumetric loading rate of 487 g COD·m^{-3}·d^{-1} and an areal loading rate of 5.4 g COD·m^{-2}·d^{-1}. In a moving bed biofilm reactor, Aygun *et al.* [3] obtained the biomass yield of 0.12 kg TSS·kg COD^{-1} at the organic loading rate of 6 g COD·m^{-2}·d^{-1}.

Table 3. The sludge yield (Y) and load of COD removed from reactors I and II at different HRTs (in series of the changeable internal circulation (q) data are given for q = 40 dm^3·h^{-1})

Reactor	HRT [min]	Sludge yield (Y) [g TSS·g COD^{-1}]	Load of COD removed [g COD·d^{-1}]
I	70	0.138	0.50
	60	0.117	0.50
	30	0.074	1.68
	15	0.066	3.92
II	70	0.175	1.85
	60	0.149	2.74
	30	0.107	3.73

In the present study the sludge yield was calculated with the assumption that the total excess biomass was washed out of the reactors. As shown in Table 3, the sludge yield (Y) decreased with the shortening of HRT and increase in VLR. In reactor I, a 7.5-fold increase in VLR caused a decrease in Y of 52%. In the case of reactor II, a decline in Y of 39% resulted from a 3.1-fold increase in VLR. The load of COD removed increased along with the shortening of HRT from 0.5 to 3.92 g COD·d^{-1} in reactor I, and from 1.85 to 3.73 g COD·d^{-1} in reactor II. The phenomenon of a decrease in sludge yield following an increase in VLR may be caused by a change of aerobic and anaerobic growth conditions, which has not been documented and requires further research. At high VLR and short HRT anoxic or anaerobic zones could have formed in the reactors. Aerobic yield is higher than the corresponding anoxic yield [10], therefore in our investigations the reduction of sludge yield by an increase in VLR was observed.

Additionally, the hydrodynamic conditions in the reactor and biofilm structure may explain the experimental results given above. At higher substrate loading a denser biofilm with lower porosities is formed [28]. According to Zhan *et al.* [30], increasing substrate loading favors an increase in the thickness of the active biofilm. The thicker the biofilm, the greater the amount of extracellular polymeric substances (EPS) produced [31]. The traditional view is that organic compounds are either shunted to the electron acceptor to generate energy or are converted to biomass. However, when a significant part of them is shunted to EPS (extracellular polymeric substances) or SMP (soluble microbial products) formation, the amount of organic compounds available for synthesizing active biomass is reduced, and active biomass yield and specific growth rate decline. Therefore, ignoring EPS and/or SMP can lead to a general overestimation of cellular growth rates [18].

The capacity of internal circulation in reactors with biomass immobilized in stationary carriers can be used to control biomass production. Our studies indicate that a change of internal circulation from 20 to 60 $dm^3 \cdot h^{-1}$ affects the sludge yield (Y) (Fig. 2). In reactor I, at a HRT of 60 min Y decreased by 71.4%. Similarly, in reactor II, at a HRT of 70 min Y decreased by 44.4%, at a HRT of 60 min by 20.8%, and at a HRT of 30 min by 36.8%. The circulation causes the dilution of the influent, so the higher the wastewater dilution the lower the sludge yield (Y). The decrease in biomass yield was probably the result of an increase in hydraulic loadings of carriers because of circulation. In order to explain the low amount of biomass washed out of the reactors following the increase in wastewater flow, the Laspidou, Rittmann [19] hypothesis can be used. They stated that the continual exposure to physical forces from the flowing water causes the biofilm solids to consolidate or pack more densely as water is squeezed out. Additionally, according to Vieira *et al.* [26], the bacteria reinforce the EPS matrix to protect themselves against the more aggressive forces from the surrounding liquid.

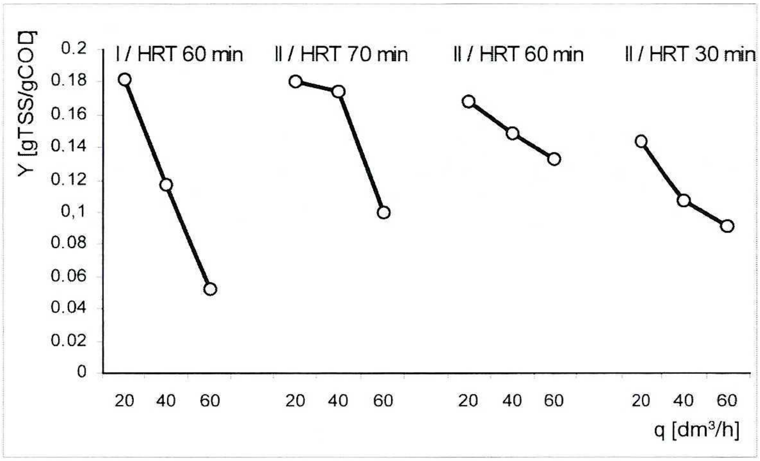


Fig. 2. Sludge yield (Y) for reactors I and II at different internal circulation capacity (q)

The changeable contribution of particular fractions of organic compounds in wastewater can be one of the factors affecting the values of the sludge yield (Y). The values of Y in reactor II were higher compared to the values obtained in reactor I. In the influent to reactor I, soluble organic compounds accounted for 27.4% of total COD, the remaining being particulate. The influent to reactor II was characterized by the amount of soluble COD, which increased to 55.3% compared to the influent to reactor I. The contribution of particular fractions of soluble and particulate compounds was also different (Fig. 3). The differences in the composition of raw wastewater flowing into both reactors are due to the fact that municipal wastewater was taken directly from a sewer pipe inspection chamber each day, and its composition changed during the experimental period. In Guellil *et al.* [14], the wastewater composition was similar to that flowing into reactor I. Particulate, colloidal and soluble proportions were found to be 45, 31 and 24% of total COD, respectively. According to Çokgör *et al.* [11], the average total soluble fraction was determined as 30%, and the average readily biodegradable fraction as 9% of the total COD content of domestic sewage. In our research, the higher biodegradable soluble fraction and lower particulate fraction in the influent to reactor II were probably the reasons for direct assimilation of organic compounds, omitting hydrolysis. Therefore, a higher biomass production was obtained in reactor II in comparison to reactor I at equivalent HRTs (Tab. 3). A major part of the organic matter in municipal wastewater is suspended and is partly hydrolyzed during the biological treatment processes. The products of hydrolysis supply organic matter for the microbial metabolism [15].

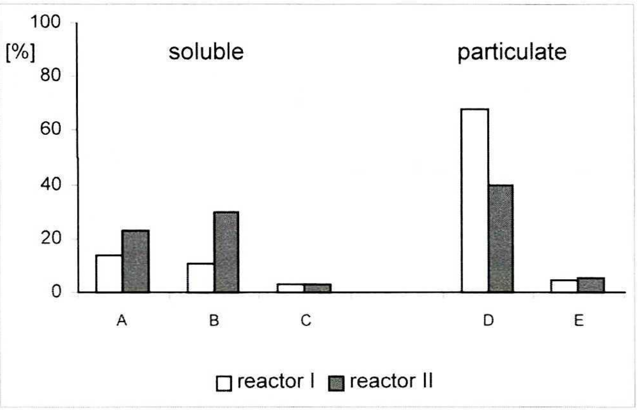


Fig. 3. Contribution of organic compound fractions in the influent (A – very readily biodegradable, B – readily biodegradable, C – non-biodegradable or slowly biodegradable, D – biodegradable, E – non-biodegradable or slowly biodegradable)

The internal carrier structure could have been a further factor affecting the higher values of sludge yield in reactor II. In the three-channeled carrier I the internal channels occupied about 50% of the total volume, whereas in the eight-channeled carrier II the internal channels accounted for about 44% of the total volume. According to Matsumura *et al.* [21], the proper balance between the active surface of a carrier and open space is very important, since it influences the rate of mass transport.

In our study, the increase in VLR in reactor I from 6.5 to 48.8 g $COD \cdot dm^{-3} \cdot d^{-1}$ caused a change in oxygen uptake rate by the immobilized biomass for substrate respiration. The rate decreased from 0.116 to 0.045 mg $O_2 \cdot mg\ TSS^{-1} \cdot h^{-1}$. In reactor II, despite an increase in VLR from 5.4 to 16.6 g $COD \cdot dm^{-3} \cdot d^{-1}$, the rates of substrate respiration were similar in the range from 0.043 to 0.054 mg $O_2 \cdot$mg $TSS^{-1} \cdot h^{-1}$ (Tab. 4). In investigations by Witzig *et al.* [29], sludge samples taken from the membrane reactor consumed the dissolved oxygen at the rates of 0.032–0.036 mg $O_2 \cdot$g $MLVSS^{-1} \cdot min^{-1}$. Rostron *et al.* [25] determined the respiration activity of biomass immobilized in polyurethane foam. The respiration rate increased by about 400% when the HRT of the reactor was reduced from 1.5 to 1 d. The rate decreased almost three-fold when the HRT was lowered to 0.5 d, possibly due to an increase in shear forces at the greater flow rate.

Table 4. Oxygen uptake rate for substrate and endogenous respiration at different HRTs and VLRs

Reactor	HRT [min]	VLR [g COD$\cdot dm^{-3} \cdot d^{-1}$]	Rate of substrate respiration [mg $O_2 \cdot$mg $TSS^{-1} \cdot h^{-1}$]	Rate of endogenous respiration [mg $O_2 \cdot$mg $TSS^{-1} \cdot h^{-1}$]
I	70	6.5	0.116	0.028
	60	8.0	0.100	0.033
	30	20.8	0.079	0.096
	15	48.8	0.045	0.057
II	70	5.4	0.051	0.024
	60	5.8	0.054	0.048
	30	16.6	0.043	0.048

Total respiration activity includes the oxygen uptake for substrate respiration, endogenous respiration and for ammonia oxidation. In reactor I, at a HRT of 70 and 60 min, endogenous activity of the immobilized biomass accounted for 13–15% of total respiration activity (Table 4; the oxygen consumption for nitrification is not shown). A shortening of a HRT to 30 and 15 min caused an increase in the participation of endogenous respiration to over 30%. In reactor II, the participation of endogenous respiration in total oxygen uptake increased from 14 to 39% following a shortening of HRT from 70 to 30 min. Van Loosdrecht, Henze [20] stated that the endogenous respiration in many cases accounted for more than 50% of the total oxygen consumption.

CONCLUSIONS

In reactors with biomass immobilized in a stationary filling, the values of the sludge yield decreased by increasing the volumetric loading rate. This may have been connected with the change of aerobic conditions in the immobilized biomass. The values of the sludge yield depended on wastewater composition (COD fractions) and the internal structures of the carriers (percentage of free space in the total volume of each carrier).

In reactors with biomass immobilized in a stationary filling, an increase in the capacity of internal circulation from 20 to 60 $dm^3 \cdot h^{-1}$ reduced the sludge yield from 20 to 70%.

An increase in the ratio of endogenous respiration to substrate respiration by immobilized biomass corresponded to a decrease in the sludge yield.

NOMENCLATURE

q – capacity of internal circulation [$\mathrm{dm^3 \cdot h^{-1}}$],
HRT – hydraulic retention time [min],
SLR – carrier surface loading rate [$\mathrm{g\ COD \cdot m^{-2} \cdot d^{-1}}$],
VLR – volumetric loading rate [$\mathrm{g\ COD \cdot dm^{-3} \cdot d^{-1}}$],
DO – concentration of dissolved oxygen [$\mathrm{mg\ O_2 \cdot dm^{-3}}$],
Y – sludge yield [$\mathrm{g\ TSS \cdot g\ COD^{-1}}$],
TSS – total suspended solids [$\mathrm{g \cdot m^{-3}}$],
VSS – volatile suspended solids [$\mathrm{g \cdot m^{-3}}$],
MLSS – mixed liquor suspended solids [$\mathrm{g \cdot m^{-3}}$],
MLVSS – mixed liquor volatile suspended solids [$\mathrm{g \cdot m^{-3}}$].

REFERENCES

[1] Adham S., P. Gagliardo, L. Boulos, J. Oppenheimer, R. Trussell: *Feasibility of the membrane bioreactor process for water reclamation*, Water Sci. Technol., **43**, 203–209 (2001).

[2] Aspegren H., U. Nyberg, B. Andersson, S. Gotthardsson, J.C. Jansen: *Post denitrification in a moving bed biofilm reactor process*, Water Sci. Technol., **38**, 31–38 (1998).

[3] Aygun A., B. Nas, A. Berktay: *Influence of high organic loading rates on COD removal and sludge production in moving bed biofilm reactor*, Environ. Eng. Sci., **25**, 1311–1316 (2008).

[4] Barnard J.L.: *Design of wastewater treatment plant with activated sludge removing nutrients*, [in:] Philosophy of designing and the exploitation of wastewater treatment plant, Kraków 2000, pp. 13–59.

[5] Benthum W.A.J. van, M.C.M. van Loosdrecht, J.J. Heijnen: *Control of heterotrophic layer formation on nitrifying biofilms in a biofilm airlift suspension reactor*, Biotechnol. Bioeng., **53**, 397–405 (1997).

[6] Canales A., A. Pareilleux, J.L. Rols, G. Goma, A. Huyard: *Decreased sludge production strategy for domestic wastewater treatment*, Water Sci. Technol., **30**, 97–106 (1994).

[7] Chiemchaisri C., K. Yamamoto: *Biological nitrogen removal under low temperature in a membrane separation bioreactor*, Water Sci. Technol., **28**, 325–333 (1993).

[8] Choo K.H., H.D. Stensel: *Sequencing batch membrane reactor treatment: nitrogen removal and membrane fouling evaluation*, Water Environ. Res., **72**, 490–498 (2000).

[9] Cicek N., H. Winnen, M.T. Suidan, B.E. Wrenn, V. Urbain, J. Manem: *Effectiveness of the membrane bioreactor in the biodegradation of high molecular weight compounds*, Water Res., **32**, 1553–1563 (1998).

[10] Copp J.B., P.L. Dold: *Comparing sludge production under aerobic and anoxic conditions*, Water Sci. Technol., **38**, 285–294 (1998).

[11] Çokgör E.U., S. Sözen, D. Orhon, M. Henze: *Respirometric analysis of activated sludge behaviour – I. Assessment of the readily biodegradable substrate*, Water Res., **32**, 461–475 (1998).

[12] Gander M.A., B. Jefferson, S.J. Judd: *Membrane bioreactors for use in small wastewater treatment plants: membrane materials and effluent quality*, Water Sci. Technol., **41**, 205–211 (2000).

[13] Ghyoot W., W. Verstraete: *Reduced sludge production in a two-stage membrane-assisted bioreactor*, Water Res., **34**, 205–215 (2000).

[14] Guellil A., F. Thomas, J.C. Block, J.L. Bersillon, P. Ginestet: *Transfer of organic matter between wastewater and activated sludge flocs*, Water Res., **35**, 143–150 (2001).

[15] Henze M., C. Mladenovski: *Hydrolysis of particulate substrate by activated sludge under aerobic, anoxic and anaerobic conditions*, Water Res., **25**, 61–64 (1991).

[16] Jefferson B., A.L. Laine, S.J. Judd, T. Stephenson: *Membrane bioreactors and their role in wastewater reuse*, Water Sci. Technol., **41**, 197–204 (2000).

[17] Krauth K., K.F. Staab: *Pressurized bioreactor with membrane filtration for wastewater treatment*, Water Res., **27**, 405–411 (1993).

[18] Laspidou C.S., B.E. Rittmann: *A unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass*, Water Res., **36**, 2711–2720 (2002).

[19] Laspidou C.S., B.E. Rittmann: *Modeling the development of biofilm density including active bacteria, inert biomass, and extracellular polymeric substances*, Water Res., **38**, 3349–3361 (2004).

[20] Loosdrecht M.C.M. van, M. Henze: *Maintenance, endogenous respiration, lysis, decay and predation*, Water Sci. Technol., **39**, 107–117 (1999).

[21] Matsumura M., T. Yamamoto, P. Wang, K. Shinabe, K. Yasuda: *Rapid nitrification with immobilized cell using macro-porous cellulose carrier*, Water Res., **31**, 1027–1034 (1997).

[22] Mayhew M., T. Stephenson: *Biomass yield reduction: is biochemical manipulation possible without affecting activated sludge process efficiency?*, Water Sci. Technol., **38**, 137–144 (1998).

[23] Polish Standards: Polish Committee for Standardization, available from http://www.pkn.pl.

[24] Rosenberger S., U. Krüger, R. Witzig, W. Manz, M. Szewzyk, M. Kraume: *Performance of a bioreactor with submerged membranes for aerobic treatment of municipal wastewater*, Water Res., **36**, 413–420 (2002).

[25] Rostron W.M., D.C. Stuckley, A.A. Young: *Nitrification of high strength ammonia wastewaters: comparative study of immobilisation media*, Water Res., **35**, 1169–1178 (2001).

[26] Vieira M.J., L.F. Melo, M.M. Pinheiro: *Biofilm formations: hydrodynamic effects on internal diffusion and structure*, Biofouling, **7**, 67–80 (1993).

[27] Wang B., J. Li, L. Wang, M. Nie, J. Li: *Mechanism of phosphorus removal by SBR submerged biofilm system*, Water Res., **32**, 2633–2638 (1998).

[28] Wijeyekoon S., T. Mino, H. Satoh, T. Matsuo: *Effects of substrate loading rate on biofilm structure*, Water Res., **38**, 2479–2488 (2004).

[29] Witzig R., W. Manz, S. Rosenberger, U. Krüger, M. Kraume, U. Szewzyk: *Microbiological aspects of a bioreactor with submerged membranes for aerobic treatment of municipal wastewater*, Water Res., **36**, 394–402 (2002).

[30] Zhan X.M., M. Rodgers, E. O'Reilly: *Biofilm growth and characteristics in an alternating pumped sequencing batch biofilm reactor (APSBBR)*, Water Res., **40**, 817–825 (2006).

[31] Zhang X., P.L. Bishop: *Spatial distribution of extracellular polymeric substances in biofilms*, J. Environ. Eng., **127**, 850–856 (2001).

Received: February 2, 2009; accepted: March 30, 2010.

PRZYROST BIOMASY W POROWATYCH NOŚNIKACH CERAMICZNYCH PODCZAS OCZYSZCZANIA ŚCIEKÓW KOMUNALNYCH

Dwa porowate nośniki ceramiczne z unieruchomionym osadem czynnym stanowiły stacjonarne wypełnienie bioreaktorów, w których oczyszczaniu poddawano ścieki komunalne przy hydraulicznym czasie zatrzymania od 15 do 70 min i cyrkulacji wewnętrznej równej 20, 40 i 60 $dm^3 \cdot h^{-1}$. W zależności od hydraulicznego czasu zatrzymania, współczynnik przyrostu biomasy zmieniał się z 0,138 do 0,066 g $TSS \cdot g\ COD^{-1}$ w reaktorze I oraz z 0,175 do 0,107 g $TSS \cdot g\ COD^{-1}$ w reaktorze II. Zwiększenie obciążenia objętości reaktorów ładunkiem zanieczyszczeń oraz wydajności cyrkulacji wewnętrznej powodowało zmniejszenie przyrostu biomasy. Spadek przyrostu biomasy odpowiadał wzrostowi stosunku oddychania endogennego i substratowego unieruchomionej biomasy.