CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

No. 2 2007

PREVIOUS INVESTIGATIONS ON THE INFLUENCE OF OXYGEN CONCENTRATION ON NITROGEN REMOVAL EFFICIENCY IN A HYBRID MOVING BED SEQUENCING BATCH BIOFILM REACTOR (MBSBBR)

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The paper presents preliminary results of the research on the efficiency nitrogen removal in a hybrid sequencing batch reactor MBSBBR operating at low dissolved oxygen (DO) concentration ranging between 0,5 and 2 mg O_2/l. The study was carried out in a pilot scale model of SBR with a total volume of 35 liters, filled with carrier media up to the volumetric ratio 7,5 % of the fill volume. A high efficiency of COD removal, obtained at DO concentration of 0,5÷1,0 mg O_2/l, creates possibilities for a substantial reduction of exploatation costs for wastewater treatment plants on MBSBBR reactors. The analysis of the influence of a preset DO level on nitrogen transformation processes was found that together with an increase of DO concentration in the aerobic phases of the cycle an increase of the nitrification rate and decrease of the simultaneous denitrification rate can be observed. The highest efficiency of nitrogen compounds removal was reached at DO concentration of 1,0÷1,5 mg O_2/l. The conducted survey has confirmed that a DO concentration is one of the criterion-parameters for the process of simultaneous denitrification in aerobic phases.

Keywords: dissolved oxygen concentration, MBSBBR, nitrogen removal

1. INTRODUCTION

Oxygen is a factor that conditions the progress of many biological wastewater treatment processes, and the energy that is required for its supply makes a substantial position in the exploitation cost balance of a wastewater treatment plant.

In continuous flow Moving Bed Biofilm Reactors (MBBR) a DO concentration is next to the $N\text{-}NH_4^+$ concentration a limiting factor for nitrification (Ødegaard and Rusten, 1993; Hem et al., 1994). When a proportion between DO

and ammonia-N concentrations takes a value below 2, then the rate of nitrification is dependent only on the oxygen concentration. The boundary value for DO/ammonia-N ratio, at which DO concentration has a decisive influence on the nitrification rate was determined to be equal to 3 g O_2/ g NH_4^+-N. Based on the laboratory scale experiments (Hem et al., 1994), half-technical scale experiments (Ødegaard and Rusten, 1993; Hem et al., 1994; Pastorelli et al., 1997; Rusten et al., 2000) as well as technical scale experiments (Rusten et al., 1994) it was demonstrated, that the nitrification rate stayed in a linear correlation with DO concentration in the bulk liquid. It was assumed, that the main mechanism determining the process rate is diffusion between the solid and the liquid phase. Existence of such a "strong" relationship between the nitrification rate and the dissolved oxygen concentration is recognized as one of the shortcomings of Moving Bed Biofilm Reactors, because in comparison to other, conventional bioreactors with activated sludge, they demand higher DO concentration levels, and therefore have higher air-supply requirements.

Sequencing Batch Reactors using the Moving Bed technology (MBSBBR) allow, unlike the continuous flow systems (MBBR) to obtain a high C, N and P removal efficiency in only one tank. Thanks to the possibility to periodically change the milieu conditions in the tank, these reactors can work as an anaerobic, anoxic and aerobic chamber and also as a final clarifier. A proper control of DO concentration in each consecutive phase of a cycle allows to decrease the wastewater treatment costs and at the same time to obtain a high efficiency of integrated nitrogen and phosphorus removal at the limited availability of organic substrates. Based on the research on nitrogen transition processes in MBSBBRs, Pastorelli et al. (1999) indicated, that a fundamental share in the nitrogen elimination from wastewater has a process of simultaneous nitrification/denitrification which takes place in aerobic phases. An increase of Food to Mass ratio (F/M) in the reactor caused a rise of the removal rate of organic substrates in anaerobic conditions, what then led to a decrease of organic load in aerobic conditions and therefore caused an increase of ammonia utilization rate. This process occurred without any detection of nitrates as products of ammonia oxidation, and therefore was classified as simultaneous nitrification/denitrification. The authors framed a hypothesis, that the majority of biodegradable COD was taken up and stored during the anaerobic phases and this process was led by Denitrifying Polyphosphate Accumulating Organisms-DPAO inhabiting the inner parts of biofilm. In the aerobic phase these microorganisms utilized nitrates as electron acceptors for the oxidation of internally stored organic substrates and reducing them to gaseous nitrogen.

The results of research of Pastorelli et al. (1999) were confirmed by Helness and Ødegaard (2001). In an experiment, where at the beginning of the aerobic phase, a specified amount of nitrates was added, an increase of phosphorus

removal was observed. This confirmed a thesis, that the denitrification was then coupled with accumulation of phosphates. Furthermore it was also demonstrated, that the demand for COD for the elimination of N and P through the simultaneous P-PO_4 uptake and denitrification carried on by DPAO is smaller as for the aerobic accumulation of phosphates by Polyphosphate Accumulating Organisms (PAO) and „separate" denitrification led by denitrifiers unable to take up phosphates. Based on the obtained results, the following conclusion was drawn: In order to obtain a highly efficient removal of N and P in a MBSBBR, duration time of the anaerobic phase should assure an almost complete removal of easily biodegradable COD, whereas duration time of the aerobic phase should allow a complete nitrification. At the same time, a total reactor's loading rate should be such high, as to maintain the biomass growth. The authors submitted a thesis, that the main factor influencing an efficient integrated removal of N and P is the ratio between the anaerobic phase duration time and the overall cycle length.

Nitrogen removal through the process of simultaneous nitrification/denitrification in aerobic phases of a cycle was also observed by Podedworna and Żubrowska-Sudoł (2003), Żubrowska-Sudoł (2003). These authoresses, contrary to the above-mentioned authors, conducted their surveys in a hybrid bioreactor (a combination of activated sludge and biofilm growing on freely moving carriers). In their own investigations, they observed, that one of the factors influencing an efficiency of simultaneous nitrification/denitrification is the oxygen concentration. They also submitted a proposition that the wastewater treatment in a hybrid MBSBBR reactor with DO concentrations in aerobic phases below 2 mg O_2/l, allows to remove a substantial load of nitrogen through the process of simultaneous nitrification/denitrifying dephosphatation, what in consequence leads to a lower demand for organic substrates, a decrease in biomass production and a reduction of oxygen consumption (which is tantamount to lower energy usage).

This paper presents preliminary results of the investigations of an influence of oxygen concentration on the efficiency of nitrogen removal in a hybrid MBBSBBR reactor.

2. METHODS

The study was carried out in a pilot scale model of Sequencing Batch Reactor (SBR) made of plexiglass (cuboid shape, LxWxH = 270x270x500 mm) with a total volume of 35 liters. The reactor was filled with carrier media up to the volumetric ratio of 7,5 % of the fill volume (Figure 1). The support media used in the study were mobile plastic cylindrical elements (5 mm in diameter, 8 mm length) of 1,1 g/l specific gravity and a total specific area of 800 m^2/m^3.

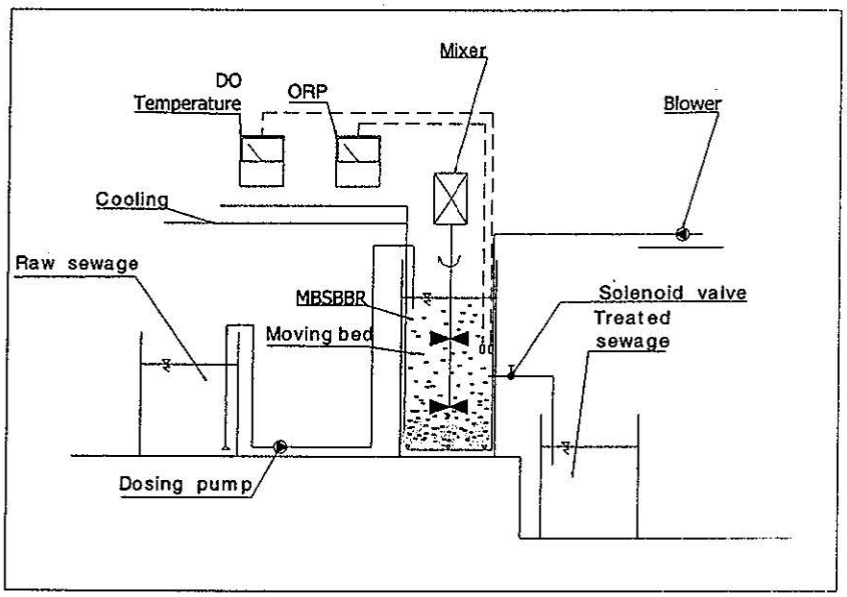

Figure 1 Schematic representation of the laboratory apparatus.

The invested experimental set-up worked in a continuous manner throughout 420 days, during which 6 experiment series were performed (Table 1). These series were characterized by different boundary conditions. The reactor was fed with synthetic sewage prepared from peptone, starch, glucose, glycerol, acetic acid, ammonium acetate, ammonium chloride and phosphorus salts. The pH of this sewage was at each time corrected to a value of 7,4÷7,7 with 20% NaOH.

This paper presents the results obtained during the 3rd experiment series. The experiment was carried out for four following dissolved oxygen concentration ranges in the aerobic phases: 2,0÷3,0 mg O_2/l, 1,5÷2,0 mg O_2/l, 1,0÷1,5 mg O_2/l, 0,5÷1,0 mg O_2/l. The actual laboratory testing was at each time preceded by a period necessary for the biomass to adapt to modified aerobic conditions. The end of the adapt period was determined by the moment from which repeatable characteristics of the effluent could be noted. A scope of performed experiments included controlling the physical-chemical parameters of the influent and the effluent and carrying out the monitoring surveys that are based on controlling the variations of wastewater composition during the cycle. All the measurements were made according to the valid polish standards.

Table 1. General characteristic of research series

Series	Amount of carriers* [%]	Cycle duration time [h]	DO concentration [mg O_2/l]	COD:N	COD:P	FCOD loading rate [g COD/g ds.day]
I	without	8	2,0 ÷ 3,0	9,27 ÷ 11,0	29,1 ÷ 47,8	0,234 ÷ 0,395

II	7,5	8	2,0 ÷ 3,0	9,38 ÷ 11,8	39,6 ÷ 55,7	0,264 ÷ 0,379
III	7,5	6	0,5 ÷ 3,0	8,20 ÷ 10,5	30,2 ÷ 42,8	0,401 ÷ 0.536
IV	15	6	2,0 ÷ 3,0	9,7 ÷ 12,2	33,8 ÷ 54,2	0,362 ÷ 0,431
V i VI	7,5	6	2,0 ÷ 3,0	3,06 ÷ 9,89	10,0 ÷ 35,7	0,120 ÷ 0,367

*in relation to reactor's operating volume

The full MBSBBR cycle consisted of the following subsequent phases, which duration times were being set based on the changes of oxidation-reduction potential (ORP):

1st anaerobic phase (45 minutes) with fill (2/3 of the total volume in the cycle),
1st aerobic phase (105 minutes, including 1st stage: 30 minutes, 2nd stage: 75 minutes),
2nd anaerobic phase (30 minutes) with fill (1/3 of the total volume in the cycle),
2nd aerobic phase (60 minutes, including 1st stage: 30 minutes, 2nd stage: 30 minutes), Settle (90 minutes), Decant (15 minutes), Idle (15 minutes).

The cycle arrangement in the reactor is shown in Figure 2.
Under the term "anaerobic phases" such periods are meant, during which the reactor's content was only mixed (lack of the presence of dissolved oxygen, possibility of the presence of nitrates and nitrites as products of aerobic reactions). The period, during which the tank's content was mixed and aerated are called aerobic phases. A stage is the time between each consecutive sample collection in a given phase of a cycle.

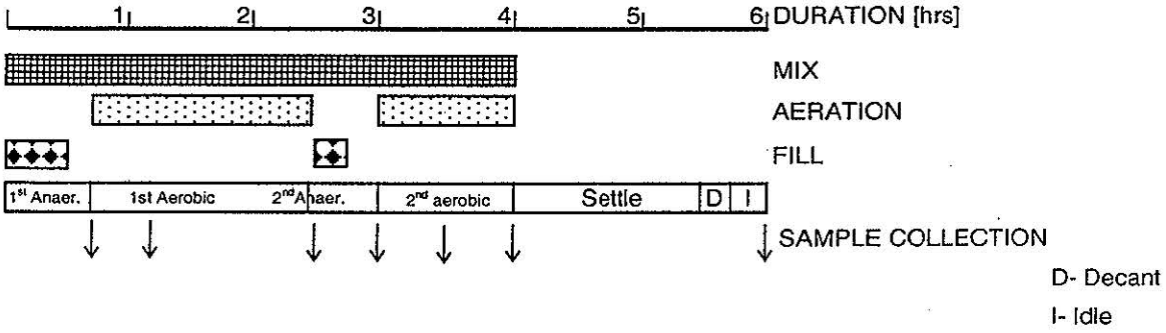

Fig. 2. Cycle arrangement in the experimental set-up

During the whole experiment from 9,5 to 11 liters of raw sewage were supplied to the reactor in each and every cycle. The volumetric exchange ratio during the entire experiment was 0,37÷0,40. Mixed liquor suspended solids

(MLSS) concentration referring to the maximum fill during the phase equaled 2,3÷2,8 g/l.

3. RESULTS AND DISCUSSION

3.1. Treatment efficiency

According to the data presented in Table 2, a comparable high efficiency (95,6÷98 %) of organics removal was obtained for all ranges of DO. Unlike for the organics, differentiated efficiencies of nitrogen and phosphorus removal were however observed for different DO levels.

Table 2. Ranges of the analyzed wastewater component concentrations in the raw sewage and in the effluent and the efficiencies of their removal at different dissolved oxygen concentrations in aerobic phases

	Raw sewage	Effluent quality depending on DO concentration in the reactor [mgO_2/l]			
		2,0 ÷ 3,0	1,5 ÷ 2,0	1,0 ÷ 1,5	0,5÷ 1,0
COD [mgO_2/l]	623 ÷ 793	15,5 ÷ 28,0	19,5 ÷ 22,7	16,8 ÷ 28,8	21,3 ÷ 29,3
E_{COD} [%]		96,3 ÷ 98,0	96,8 ÷ 97,4	95,6 ÷ 97,6	95,6 ÷ 97,8
N-NTK [mg N-NTK/l]	69,5 ÷ 75,8	1,04 ÷ 2,40	1,20 ÷ 2,60	1,40 ÷ 3,80	17,30 ÷ 22,60
$E_{N\text{-}NTK}$ [%]		96,7 ÷ 98,7	96,5 ÷ 98,4	94,5 ÷ 98,0	69,9 ÷ 76,7
$N\text{-}NH_4^+$ mg $N\text{-}NH_4^+/l$	48,3 ÷ 52,3	0 ÷ 0,18	0,10 ÷ 0,20	0,07 ÷ 1,16	14,50 ÷ 17,00
$E_{N\text{-}NH4^+}$ [%]		99,6 ÷ 100	99,6 ÷ 99,8	97,6 ÷ 99,9	66 ÷ 71,3
TN mg TN/l	69,8 ÷ 76,3	9,7 ÷ 17,4	11 ÷ 13,2	5,2 ÷ 9,30	18,8 ÷ 24
E_{TN} [%]		76,1 ÷ 87,2	82 ÷ 85,3	86,8 ÷ 93,1	67,9 ÷ 74,6
$N\text{-}NO_3^-$ mg $N\text{-}NO_3^-/l$		8,7 ÷ 15	9,7 ÷ 11,1	2,26 ÷ 6,37	0,39 ÷ 0,50
$P\text{-}PO_4^{3-}$ mg $P\text{-}PO_4^{3-}/l$	15,8 ÷ 18,6	0,05 ÷ 0,09	0,19 ÷ 0,26	0,61 ÷ 0,88	4,27 ÷ 6,45
$E_{P\text{-}PO4^{3-}}$ [%]		99,5 ÷ 99,8	98,5 ÷ 98,9	94,7 ÷ 96,5	59,2 ÷ 74,7
TP mg TP/l	17,1 ÷ 22,7	0,09 ÷ 1,14	3,98 ÷ 6,08	3,56 ÷ 4,32	6,12 ÷ 8,78
E_{TP} [%]		94,7 ÷ 99	73,3 ÷ 85	78,1 ÷ 83,1	51,7 ÷ 66,7

The highest efficiency of total nitrogen (TN) removal was reached at DO concentration of about 1÷1,5 mgO_2/l. The concentration of TN in the effluent at that time fitted in the range of 5,2 to 9,3 mg N/l. A substantial increase of TN in the outflow (18,8÷24 mg N/l), being a direct consequence of a low efficiency of ammonia-N removal, was observed at DO equal to 0,5÷1 mg O_2/l. A fully satis-

factory elimination of ammonia nitrogen (97,6÷100 %) was reached in configurations operating at oxygen concentrations above 1 mg O_2/l.
From the data presented in Table 2 it also appears, that the highest reduction of orthophosphates ($P\text{-}PO_4^{3-}$), equal to 99,8%, was observed for the set-up working at DO concentrations of about 2,0÷3,0 mg O_2/l. A little lower efficiency of biological excess phosphorus removal was recorded for DO concentration 1÷2 mg O_2/l. Lowering DO to the level of 0,5÷1,0 mg O_2/l resulted in a substantial reduction in the efficiency of $P\text{-}PO_4^{3-}$ removal.

Analyzing the efficiency of total phosphorus (TP) removal we have found, that contrary to the efficiency of orthophosphates removal, a considerable reduction of TP occurred even at DO concentrations as low as 1,5 ÷ 2,0 mg O_2/l. This indicates to a decrease in the organic phosphorus removal efficiency. For organic phosphorus belongs to a particulate fraction of total phosphorus, its removal from wastewater in a biological process can occur as a result of adsorption on activated sludge flocs or as a result of earlier hydrolysis to orthophosphates, and next of its removal in a process biological excess phosphorus removal. The results being presented indicate that in the examined laboratory set-up, organic phosphorus was removed both mechanically and biologically. Most probably the intensity of hydrolysis of particulate fractions of phosphorus was determined by the dissolved oxygen concentration.

3.2. Influence of DO concentration on the efficiency of nitrogen removal

Exemplary changes in the concentrations of consecutive nitrogen forms in the subsequent stages of a cycle, related to the theoretical concentration values in the anaerobic phases with wastewater dosage is shown in Figure 3. Theoretical concentration values were calculated from the loads remaining in the reactor after the previous treatment phase plus the load that was coming with the influent. The theoretical concentrations were marked with filled markers respectively for the 1st and the 2nd anaerobic phase and placed on the axes x = 0 and x = 2,5. From the obtained character of changes of consecutive nitrogen forms in aerobic phases it appears that for DO concentration levels equal to: 2,0÷3,0 mg O_2/l, 1,5÷2,0 mg O_2/l, 1,0÷1,5 mg O_2/l similar percent reductions of ammonia-N and TKN were obtained. Together with the increase of DO concentration, the oxidized forms of nitrogen increased out of proportion to the reduction of TKN. As a consequence of this fact a concentration of TN increased (in reference to the former stage of treatment), despite a zero inflow of raw sewage. Based on the conducted observations it was concluded, that in the performed experiment higher values of DO concentration stimulated a process of biomass lysis, which then caused a release of organic nitrogen to the bulk liquid. Due to favorable aerobic conditions the organic nitrogen was subject to ammonification and subsequent nitrification, what caused an increase of oxidized forms of nitrogen in

the reactor. During wastewater treatment at DO concentrations between 0,5 and 1,0 mg O_2/l, the recorded loss of TKN was accompanied by only slight „production" of N-NO_x (N-NO_2^- +N-NO_3^-), what reflects highly efficient nitrogen elimination in aerobic conditions. However the ammonia nitrogen concentrations present in the later part of aerobic phases (remaining within the range of 15,9÷19,0 mg N-NN_4^+/l and 15,0÷18,6 mg N-NN_4^+/l for the 1st and the 2nd p

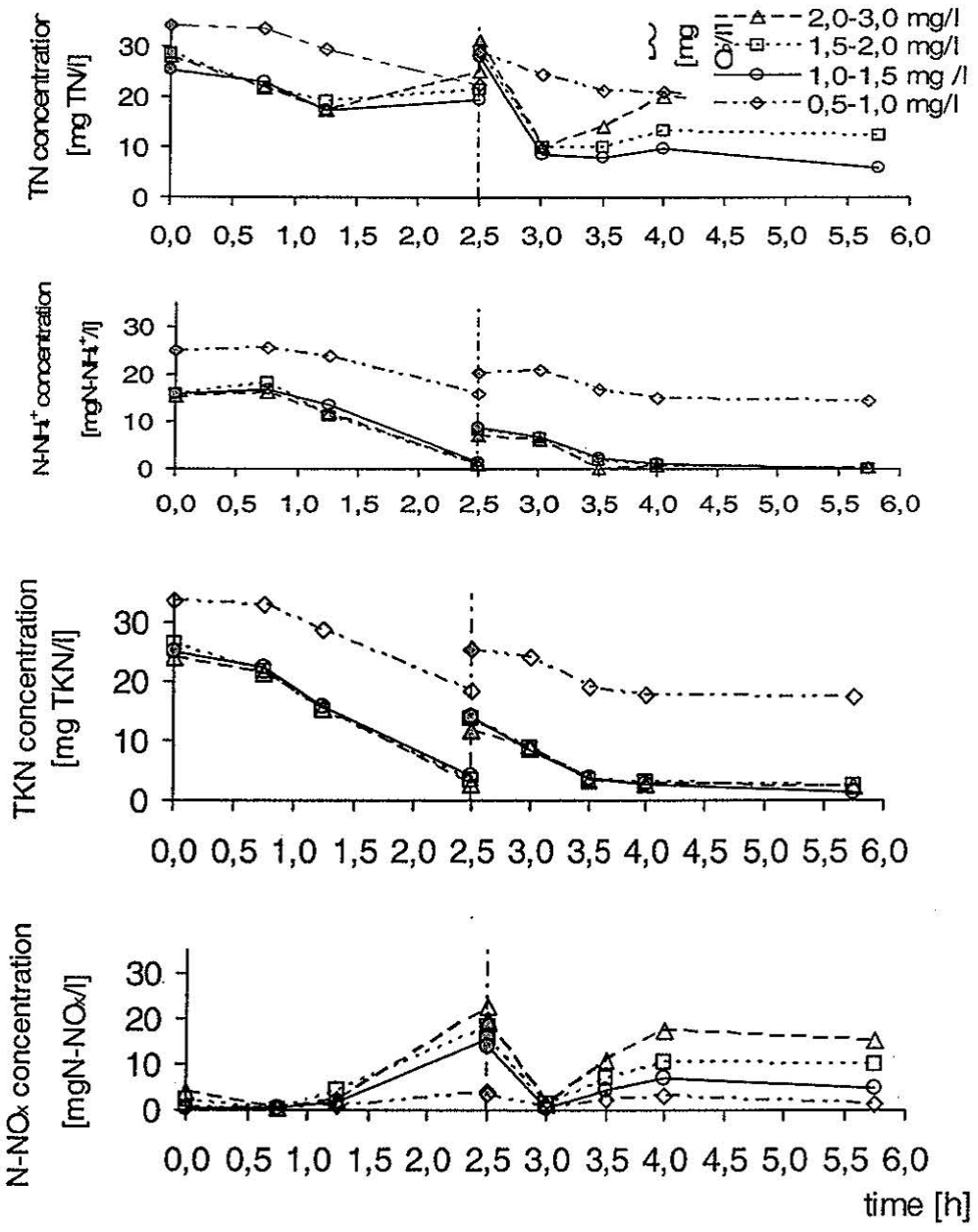

Fig. 3. Exemplary changes in the concentrations of Total Nitrogen, Ammonia-Nitrogen, Total Kjeldahl Nitrogen, Nitrates and Nitrites in the subsequent stages of a cycle, related to the theoretical concentration values in the anaerobic phases with wastewater dosage.

Table 3. Ranges of the average daily nitrogen transformation rates, efficiencies of simultaneous denitrification and percent reductions of Total Nitrogen, related to raw sewage in aerobic phases at different DO concentration levels.

Phase		DO [mg O_2/l]	$U_{ox\ N\text{-}NH_4^+}$ Ammonia oxidation daily rate [mg $N\text{-}NH_4^+$/ (g MLSS· day)]	$U_{sim.den.}$ Simultaneous denitrification daily rate [mg TN/ (g MLSS· day)]	$E_{sim.den.}$ (1) Efficiency of simultaneous denitrification [%]	E_{TN} Percent reduction of Total Nitrogen compared to the influent [%]
1st Aerobic	1st Stage	2,0÷3,0	7,90 ÷ 11,78	5,77 ÷ 8,88	73 ÷ 79	76 ÷ 79
		1,5÷2,0	8,41 ÷ 10,28	4,47 ÷ 6,40	71 ÷ 76	69 ÷ 73
		1,0÷1,5	8,68 ÷ 10,01	7,22 ÷ 8,34	83 ÷88	66 ÷ 68
		0,5÷1,0	2,31 ÷ 6,79	2,14 ÷ 6,07	89 ÷91	53 ÷ 54
	2nd Stage	2,0÷3,0	22,94 ÷ 25,38	-	-	65 ÷ 67
		1,5÷2,0	19,60 ÷ 22,42	-	-	70 ÷ 74
		1,0÷1,5	17,12 ÷ 18,81	-	-	70 ÷ 73
		0,5÷1,0	5,93 ÷ 15,40	5,93 ÷ 15,40	51 ÷ 70	62 ÷ 69
2nd Aerobic	1st Stage	2,0÷3,0	6,65 ÷ 9,78	-	-	81 ÷ 89
		1,5÷2,0	6,57 ÷ 8,77	-	-	85 ÷ 87
		1,0÷1,5	6,38 ÷ 9,53	0,89 ÷ 4,48	13 ÷ 47	87 ÷ 89
		0,5÷1,0	8,41 ÷ 10,10	5,49 ÷ 8,03	65 ÷ 84	66 ÷ 71
	2nd Stage	2,0÷3,0	8,54 ÷ 10,76	-	-	73 ÷ 79
		1,5÷2,0	9,10 ÷ 9,48	-	-	76 ÷ 81
		1,0÷1,5	3,65 ÷ 5,72	-	-	84 ÷ 86
		0,5÷1,0	2,99 ÷ 3,48	0,46 ÷ 1,39	15 ÷ 40	65 ÷ 71

(1) The efficiency of simultaneous denitrification refers to the ammonia nitrogen oxidation rate.

hase respectively) were on average 15 times higher than those analyzed for the remainder of the used DO concentration ranges. High value of $N\text{-}NH_4$, descri bing the wastewater staying in the reactor after the cycle, caused an increase of ammonia-nitrogen mass loading, which with such a low DO concentration and unchanged aerobic phase duration times (compared to the remaining variants) determined the then obtained ammonia-nitrogen elimination efficiency.

The realized experiment confirmed a thesis formed in the preliminary survey (Żubrowska-Sudoł, 2002; Podedworna and Żubrowska-Sudoł, 2003), that one of the main factors determining the efficiency of nitrogen removal in aerobic conditions is a dissolved oxygen concentration.

The pieces of data presented in Table 3 show that only for a DO concentration of 0,5÷1,0 mg O_2/l the process of a simultaneous nitrification/denitrification occurred in all stages of aerobic phases.

In the rest of cases this process was mainly present in the beginning of the 1st aerobic phase. At that time very specific aerobic conditions were present in the reactor. In the investigated phase of treatment, irrespectively of the preset DO level, we could observe a slow increase of DO concentration (despite of a continuous air supply), which at maximum reached a value of 1,4 mg O_2/l. Such a pattern of DO changes indicates a high oxygen demand and subsequently a high oxygen consumption. If we accept the hypothesis, that a process of simultaneous nitrification/denitrification is performed by the nitrifiers present in the outer layers of biofilm/activated sludge flocs as well as the denitrifying PAO_s phosphorus accumulating organisms and potentially the anaerobic ammonia oxidation microorganisms settling in the inner layers of biofilm/activated sludge flocs, we can presume that the oxygen supplied to the reactor was, due to low F/M ratio, consumed mainly by highly active nitrifying microorganisms. The products of ammonia oxidation were diffusing into the deeper layers of biofilm and/or activated sludge flocs, where thanks to the low DO concentrations in the bulk liquid, anoxic conditions subsisted. This made the reduction of nitrites and nitrates to gaseous nitrogen possible. At the second stage of the 1st and the 2nd aerobic phase, the DO concentration after the maximum value was reached, maintained at the preset level until the phase was ended. Based on the obtained results it can most likely be taken for granted, that for DO ranges equal to 2,0÷3,0 mg O_2/l, 1,5÷2,0 mg O_2/l, 1,0÷1,5 mg O_2/l the biofilm and activated sludge flocs were fully penetrated by oxygen, what had inhibited the denitrification, and the nitrification was then becoming a dominant nitrogen transformation process. A similar phenomenon was observed by Arnz et al. (2001) in the research on nutrients removal in an SBBR (Sequencing Batch Biofilm Reactor). The authors have drawn a conclusion that the process of simultaneous denitrification occurred in anoxic layers of biofilm, mainly at the beginning of aerobic phases, when DO concentration in the bulk liquid was far below saturation.

In the investigated hybrid Moving Bed Sequencing Batch Biofilm Reactor (MBSBBR), the process of simultaneous denitrification could also take place inside the activated sludge flocs. DO concentration as one of the main parameters determining the simultaneous nitrification/denitrification process in activated sludge is mentioned by i.e. Oleszkiewicz (1997), Pochana and Keller (1999), Collivignarelli and Bertanza (1999).

In their own research, the authoresses of this paper, considered a potential possibility of the existence of the following groups of organisms in the process of simultaneous denitrification:

1) Denitrifying Phosphorus Removing Organisms (DPAO);
   Based on the fact, that the aerobic phases were preceded by the anaerobic phases in which a release of orthophosphates was observed as a consequence of the storage of poly-β-hydroxy-butyrates by PAO, it was acknowledged, that the fraction of PAO capable of denitrifying (DPAO) used internal cell storage organic substrates stored during the anaerobic phases for the denitrification of nitrates produced by nitrifiers in the aerobic phases.
2) Classical heterotrophic denitrifiers;
   The limiting factor for denitrification was in this case the availability of easily biodegradable organic substrates (a substantial COD load was eliminated in the anaerobic phases). A carbon source for the classical denitrifiers could then be made of the end products of the hydrolysis of slowly biodegradable organics which self are products of the biomass lysis.
3) Microorganisms leading the process of anaerobic ammonia oxidation (ANAMMOX);
   It cannot be ruled out, that the nitrites created in the first stage of nitrification could make a substrate for the ANAMMOX biomass, and therefore contributing to oxidizing a part of ammonia-N load in the reactor. However an unmistakable indication that the ANAMMOX had really occurred in the process, would require the authors to perform Fluorescent In Situ Hybridization (FISH) experiments. Nevertheless, as an evidence of a high probability, that this process had really occurred, the following observations in the anaerobic phases can be presented: a higher loss of TKN than that arising from the biomass growth; the amount of TKN loss increasing together with a decrease in F/M ratio; rate of TKN loss in the system proportional to the biomass loading rate with nitrites and nitrates. Because even small oxygen concentrations inhibit the process of anaerobic ammonia oxidation it was accepted, that the rate of partial nitrification/ANAMMOX in the investigated set-up could not have a substantial influence on the observed loss of Total Nitrogen in the aerobic phases.

Taking the above-mentioned remarks into consideration, it was accepted, that the dominating process of nitrogen removal in the aerobic phases was a denitrifying dephosphatation. The elimination of nitrogen through simultaneous nitrification/denitrification coupled with P-removal in Sequencing Batch Biofilm Reactors (SBBR) as well as Moving Bed Sequencing Batch Biofilm Reactors (MBSBBR) was described by several workgroups: Garzón-Zúñiga and González-Martínez (1996), Helness and Ødegaard (1999, 2001), Pastorelli et al. (1999), Gieseke et al. (2002). The quoted authors assumed, that because of the fact that the organic substrates in wastewater were used up in the anaerobic phases, the process of simultaneous denitrification in the aerobic phases was most of all led by DPAO. Gieseke et al. (2002) proved that acetic acid already at the beginning of the cycle had fully penetrated the biofilm of a thickness of 500 μm. This confirmed the possibility of PHB storage in the inner parts of biofilm. It seems that the results obtained by the above-mentioned authors confirm the framed hypothesis, that in the process of simultaneous denitrification in the aerobic phases, a substantial role was played by DPAO. From the data presented in Table 4 it appears that a decrease of DO caused a reduction in the nitrification efficiency on one side, however on the other side, stimulated the process of simultaneous denitrification. The highest rate of simultaneous denitrification was noted in the 1st aerobic phase for DO in the range of 0,5÷1,0 mg O_2/l. About 72,5 % of the then oxidized ammonia was being simultaneously reduced to gaseous nitrogen, so the concentration of the oxidized forms of nitrogen at the end of the examined phase made only 18,7 % of the TN concentration. However the ammonia utilization rate at these conditions (24,0 mg N-NH_4^+/g TS·d) assured an ammonia-N elimination efficiency only at the level of 72,4 % (value related to raw wastewater), what had a direct consequence in high ammonia concentration in wastewater after the 1st aerobic phase (17,63 mg N-NH_4^+/l). Similar values of each and individual form of nitrogen for the investigated range of DO concentrations was noted also after the 2nd aerobic phase. An increase of DO to the level of 1,0÷1,5 mg O_2/l worsened the rate and the efficiency of simultaneous nitrification/denitrification, but at the same time increased the efficiency of ammonia removal. This allowed to obtain of a high TN removal efficiency after the 2nd aerobic phase. A concentration of this parameter equaled 11,3 mg TN/l, from which 67 % were nitrates (7,6 mg N-NO_3^-/l). In the wastewater, mainly after the 1st aerobic phase, the products of the 1st nitrification phase (NO_2^-) started then to appear. In case of the set-up configurations working at DO of about 2,0÷3,0 mg O_2/l and 1,5÷2,0 mg O_2/l (despite high ammonia utilization efficiency) a decrease in TN removal efficiency was noted in comparison to the set-up working at DO of about 1,0÷1,5 mg O_2/l. This was a consequence of a decrease in both the rate and the efficiency of simultanaoues denitrification, as well as of an increase in the biomass lysis intensity.

Table 4. Maximum ammonia utilization rates ($U_{(max)ox.N\text{-}NH_4^+}$) calculated for different DO concentration ranges and the corresponding rates ($U_{sim.den}$) and efficiencies ($E_{sim.den}$) of the simultaneous denitrification and TN concentrations including its each individual forms after the aerobic phases

Phase	Parameters	Units	DO concentration mg O_2/l			
			2 ÷ 3	1,5 ÷ 2	1 ÷ 1,5	0,5 ÷ 1
1st Aerobic	$U_{(max)ox.N\text{-}NH_4^+}$	[mg N-NH_4^+/ g MLSS· day]	35,7	30,8	28,3	24,0
	$U_{sim.den}$	[mg TN/ g MLSS· day]	8,9	6,4	8,3	17,4
	$E_{sim.den}$	[%]	24,9	20,8	29,4	72,5
	$N\text{-}NH_4^+$	mg N-NH_4^+/l	0,96	1,31	2,32	17,6
	$N\text{-}NO_2$	mg $N\text{-}NO_2$ /l	0,088	0,67	2,86	3,31
	$N\text{-}NO_3$	mg $N\text{-}NO_3$ /l	22,4	17,6	13,1	1,32
	TN	mg TN/l	26,1	21,5	20,9	24,6
2nd Aerobic	$U_{(max)ox.N\text{-}NH_4^+}$	[mg N-NH_4^+/ g MLSS· day]	22,1	17,4	15,6	13,3
	$U_{sim.den}$	[mg TN/ g MLSS· day]	n.o.	n.o.	4,6	8,6
	$E_{sim.den}$	[%]	-	-	29,4	64,8
	$N\text{-}NH_4^+$	mg N-NH_4^+/l	0,7	1,1	1,17	18,5
	$N\text{-}NO_2$	mg $N\text{-}NO_2$ /l	n.o.	n.o.	0,337	2,1
	$N\text{-}NO_3$	mg $N\text{-}NO_3$ /l	17,1	15	7,6	0,81
	TN	mg TN/l	19,9	17,8	11,3	23,5

n.o.- not observed

4. CONCLUSIONS

The obtained results indicated, that the highest efficiency of nitrogen compounds removal was reached at DO concentrations of 1,0 ÷ 1,5 mg O_2/l. When reduction of TN was at 86,8 ÷ 93,1 % level, concentration of this parameters in treated wastewater was than 5,2 ÷ 9,3 mg N/l. The factors determining a highly efficient elimination of TN were:

– a high efficiency of simultaneous denitrification as a consequence of the possibility of the existence of anoxic conditions in the inner layers of biofilm or/and activated sludge flocs over a substantial part of the aerobic phase.

– reduction of the sludge endogenous decay rate, which could potentially increase a load of nitrogen to the reactor.

The performed experiment indicated propriety of conducting further research, in which the process control with the use of on-line measurements of ammonia-N, orthophosphates and DO concentrations and ORP could be introduced for the optimization of the integrated removal of C, N and P. It is possible, that „smooth" changes of DO concentration in aerobic phases, depending on the current conditions in the reactor could permit a direct control of nitrogen transformation processes. For a good apprehension of the unit processes occurring during wastewater treatment in the reactor under investigation, and hence for a proper quantification of the process parameters, it is necessary to combine a physical-chemical analysis of the wastewater during treatment with a microbiological analysis aimed at the identification of all individual groups of microorganisms and the quantification of their metabolic activities depending on the treatment process conditions.

REFERENCES

1. Arnz P., Arnold E. and Wilderer P. A. (2001). *Enhanced biological phosphorus removal in a semi full-scale SBBR.* Wat. Sci. Tech., 43(3), 167-174.
2. Collivignarelli C. and Bertanza G. (1999). *Simultaneous nitrification-denitrication processses in activated sludge plants: performance and applicability.* Wat. Sci. Tech., 40(4-5), 187-194.
3. Garzón-Zúñiga M. A. and González-Martínez S. (1996). *Biological phosphate and nitrogen removal in a biofilm sequencing batch reactor.* Wat. Sci. Tech., 34(1-2), 293-301.
4. Gieske A., Arnz P., Amann R. and Schramm A. (2002). *Simultaneous P and N removal in a sequencing batch biofilm reactor: insights from reactor- and microscale investigations.* Water Res., 36, 501-509.
5. Helness H. and Ødegaard H. (1999). *Biological phosphorus removal in a sequencing batch moving bed biofilm reactor.* Wat. Sci. Technol., 40(4-5), 161-168.
6. Helness H. and Ødegaard H. (2001). *Biological phosphorus and nitrogen removal in a sequencing batch moving bed biofilm reactor.* Wat. Sci. Tech., 43(1), 233-240.
7. Hem L. J., Rusten B. and Ødegaard H. (1994). *Nitrification in a moving-bed biofilms reactor.* Water Res., 28(6), 1425-1433.
8. Ødegaard H. and Rusten B. (1993). *Norwegian experiences with nitrogen removal in a moving bed biofilm reactor.* Documentation of 9 EWPCA – ISWA Symp., Liquid Wastes Section, München (Germany), 11-14 May, pp. 205-221.

9. Pastorelli G., Andreottola G., Canziani R., Darriulat C., de Fraja Frangipane E. and Rozzi A. (1997). *Organic carbon and nitrogen removal in moving-bed biofilm reactors.* Wat. Sci. Tech., 35(6), 91-99.
10. Pastorelli G., Canziani R., Pedrazzi L. and Rozzi A. (1999). *Phosphorus and nitrogen removal in moving-bed sequencing batch biofilm reactor.* Wat. Sci. Tech. 40(4-5), 169-176.
11. Pochana K. and Keller J. (1999). *Study of factors affecting simultaneous nitrification and denitrification (SND).* Wat. Sci. Tech., 39(6), 61-68.
12. Podedworna J. and Żubrowska-Sudoł M. (2003). *Erfahrungen bei Stickstoff- und Phosphorelimination in einem SBR-Reaktor mit Fluidalfestbett.* Korrespondenz Abwasser 50(3), 321-332.
13. Rusten B., Hellström B. G., Hellström F., Sehested O., Skjelfoss E. and Svendsen B. (2000). *Pilot testing and preliminary design of moving bed biofilm reactors for nitrogen removal at FREVAR wastewater treatment plant.* Wat. Sci. Tech., 41(4-5), 13-20.
14. Rusten B., Siljudalen J.G. and Nordeidet B. (1994). *Upgarding to nitrogen removal with the KMT moving bed biofilm process.* Wat. Sci. Tech. 29(12), 185-195.
15. Żubrowska-Sudoł M. (2002). *Analiza przemian azotu w sekwencyjnym reaktorze porcjowym ze złożem zawieszonym.* GWiTS, 11, 420-426.
16. Żubrowska-Sudoł M. (2003). *Efektywność usuwania związków węgla, azotu i fosforu w reaktorze porcjowym ze złożem zawieszonym.* PhD thesis, Institute of Water Supply and Hydraulic Engineering ,Warsaw University of Technology.

OCZYSZCZANIE ŚCIEKÓW W REAKTORACH ZE ZŁOŻEM RUCHOMYM – MOŻLIWOŚCI TECHNOLOGICZNE

Streszczenie

W artykule przedstawiono wyniki badań nad wpływem stężenia tlenu na efektywność usuwania azotu w reaktorze sekwencyjnym ze złożem ruchomym (MBSBBR). Eksperyment przeprowadzono w laboratoryjnym modelu reaktora typu SBR o całkowitej objętości 35 litrów dla stężenia tlenu w zakresie 0,5÷3,0 mg O_2/l. Wypełnienie stanowiło 7,5 % czynnej objętości reaktora. Uzyskana dla stężenia tlenu 0,5÷1,0 mg O_2/l wysoka efektywność usuwania związków organicznych (ChZT) wskazuje na możliwość znaczącego obniżenia kosztów eksploatacyjnych małych oczyszczalni ścieków typu MBSBBR. Analiza wpływu stężenia tlenu na procesy przekształcania azotu wykazała, że wraz ze wzrost poziomu tego wskaźnika rosła wydajność procesu nitryfikacji, ale jednocześnie malała wydajność procesu symultanicznej denitryfikacji w fazach tlenowych cyklu. Najwyższą efektywność eliminacji azotu uzyskano dla stężenia tlenu w zakresie 1,0÷1,5 mg O_2/l. Przeprowadzone badania wykazały, że stężenie tlenu jest jednym z kryterialnych parametrów procesu symultanicznej denitryfikacji w fazach tlenowych.