Mathematical modelling of processes of reject water treatment in moving bed bioreactor

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Abstract: Efficient treatment of reject water originating from sludge digestion process was achieved by implementing a moving bed bioreactor. Since the ongoing processes in the reactor were unclear, model development was chosen in order to map them.
To describe biofilm processes a newly presented zero-dimensional biofilm model [27] was chosen. Simulation data in the study of Plattes et al. [28] were promising for municipal wastewater but it did not meet the expectations in case of wastewater with high ammonia content. Therefore four step nitrogen removal was implemented in the 0D biofilm model. Steady-state simulation showed that processes over nitrite were of great importance in the system. The results also indicated that to a certain degree ANAMMOX (anaerobic ammonia oxidation) reaction took place as well. The special structure of the moving bed bioreactor with protected microorganism colonies was assumed to be the reason for that.

Key-Words: reject water, nitrogen removal, MBBR, steady-state simulation, ANAMMOX

1. Introduction

Wastewater treatment plants produce organic sludge as wastewater is treated; this sludge must be further treated before ultimate disposal.
Disposal of sludge from wastewater treatment processes is a costly and difficult problem. First the volume of the sludge has to be decreased by removal of water, which constitutes 97–98% of the sludge; second the reduction of the volatile (organic) content of the sludge has to be achieved, which eliminates nuisance conditions by reducing putrescibility and threats to human health by reducing levels of microorganisms. Only after that can the residues be disposed.
One possible solution for reducing the amount of sludge is anaerobic digestion. Anaerobic digestion is a biological process where the biodegradable fraction of sludge or other organic residues is converted under anaerobic conditions. As a result the sludge is stabilized the volume decreased, and it can be dewatered more easily. Beside that a valuable energy source in form of biogas is produced.
There are also drawbacks of the process. The reject water from dewatering the hydrolysed sludge has to be treated as well.
Reject water flows originating from sludge treatment have a high ammonium content (typically 500–1500 g N/m^3), recycling them to the activated sludge (AS) system increases the total nitrogen load with 13-17%. But because the flows are relatively small (about 1% of the main line) cost-effective nitrogen removal in small reactors can be achieved [18]. Among the possible treatment options are the classical nitrification-denitrification, nitrification-denitrification over nitrite (SHARON – single reactor system for high ammonia removal over nitrite process) [15, 23] and nitrification combined with augmentation of the main treatment line. Another possibility is to introduce a regeneration zone where the nitrification capacity is increased by bioaugmentation [20]. Opposed to augmentation the reject water can be treated separately with the combination of SHARON-ANAMMOX processes [19] or in a moving bed biofilm reactor (MBBR) achieving specific volume enhancement.

This paper presents a model formation process of a moving bed bioreactor treating reject water of anaerobically digested sludge of a municipal wastewater treatment plant. As it will be discussed later on the pilot-scale plant had very good results in treating reject water but the processes were not clear. There are of course several analytical methods to determine the types and ratios of microorganisms and to map the ongoing processes (cf. Section 2) but these demand expensive materials and devices and time consuming experiments.
Instead mathematical modelling was used to determine the processes of the MBBR hybrid

reactor. Mathematical modelling of wastewater systems is commonly used to test conceptual understanding of systems [10, 16]. Models can be used to plan new wastewater treatment plants, optimise operation and cost-efficiency of existing WWTPs even for troubleshooting or, as it was the case in the present study, to understand the processes that take place in a complex system such as moving bed bioreactors are.

2. Sharon and Anammox processes

The nitrogen removal can be achieved via nitrite without considerable amount of organic material. In this case half of the ammonium is oxidised until nitrite (SHARON) and the nitrite reacts with the remaining ammonium (ANAMMOX). The SHARON – according to Brouwer et al. [3] and Hellinga et al. [15] – is operated without any biomass retention in a single aerated reactor at a relatively high temperature (35 °C) and pH (above 7). The process involves partial nitrification of ammonium to nitrite (Eq.(1)), and this greatly reduces the expense of aeration.

$$NH_4^+ + HCO_3 + 0.75O_2 \rightarrow \\ \rightarrow 0.5NH_4^+ + 0.5NO_2^- + CO_2 + 1.5H_2O \quad (1)$$

The ANAMMOX organisms grow with CO_2 as the sole carbon source and uses nitrite as the electron donor to produce cell material [1]. Strous et al. [31] gives the stoichiometry of anaerobic ammonium oxidation as:

$$NH_4^+ + 1.32NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow \\ \rightarrow 1.02N_2 + 0.26NO_3^- + \\ + 0.066CH_2O_{0.5}N_{0.15} + 2.03H_2O \quad (2)$$

As shown in Eq.(2) nitrite must first be produced up to a nitrite/ammonium ratio of about 1.3 [11].
ANAMMOX activity was suppressed when COD (dissolved) concentration was over 300 g/m^3 [4]. Competition between ANAMMOX and denitrifying communities was reported earlier by other researchers [4, 8]. Confirmation can be made through a detection of hydrazine, which is a unique intermediate of ANAMMOX activity, and FISH (fluorescence in situ hybridization) test [4, 12, 17]. A study was presented on using isotopic analysis of ^{15}N-labeled nitrate to define the ratio of ANAMMOX reactions to heterotrophic denitrification [32] as well.

3. Increasing volume capacity

Immobilizing microorganisms on carriers is a possibility for enhancing specific volume capacity, lowering F/M ratio demand and assisting selection of microorganisms as well. Microorganisms attach to the carrier elements with high specific surface and develop biofilm. Choosing adequate biofilm carrier surface improves the slowly reproducing microorganisms to reach appropriate ratio in the biomass.
The main aim of implementing moving bed (MBBR) systems is to combine the positive features of activated sludge and biofilm process. With MBBR systems higher specific capacity can be reached than the accessible volume capacity of traditional biofilm systems and their sludge output is low, so the recirculation of the sludge is not necessary.
The biomass is increasing on special carrier elements which can move freely in the whole volume of the reactor. The reactor can filled with carrier elements up to 70% (volumetric filling in empty reactor) in order to allow free movement [25]. The continuous movement of the carrier is achieved either by aeration or stirring. In order to prevent the carriers leaving the basin with the wastewater flowing out, a special sieve is used.
In case of aerated MBBR the actuation of the support elements is mainly done by aeration alone. The size of the air bubbles is crucial, if it is too small the bubbles are unable to agitate the carrier elements and if it is too big, the actuation becomes inefficient, the bubbles may damage the structure of the biofilm and the oxygen uptake is hindered. Therefore a special coarse bubble aerator has to be applied.

The features of the carriers determine the attachment rate, the mass and thus the performance of the biofilm. Some media that come into question: Kaldnes material, ANOX ring, polymeric bead, PUR foam cube, basalt and GAC. Compared to fixed bed support material these carrier elements provide the microorganisms greater surface at a given volume to attach and thus the performance of the system improves. The Kaldnes biofilm carrier elements are made from polyethylene with a density slightly below that of water [25]. The elements are designed to have a large protected surface area. This way, solids are not removed by attrition between the pieces thus optimal conditions are provided for the bacteria culture.

4. Overview of the examined system

The pilot-scale plant for treating reject water was established at a municipal wastewater treatment plant in Hódmezővásárhely (Hungary). The following section gives an overview of the two-stage activated sludge wastewater treatment plant and the implemented moving bed bioreactor.

4.1. The two stage AS WWTP

Fig.1 shows the scheme of the two-stage AS municipal WWTP of Hódmezővásárhely in Hungary. There are two parallel lines in the plant consisting of two aerated tanks and two clarifiers. The system does not include anaerobic or anoxic zones. Aeration is continuous and controlled in both stages based on dissolved oxygen (DO) concentration. The DO level is controlled between 0.3-0.6 g/m^3 in the first and between 3-4 g/m^3 in the second aeration basin. The plant has no primary clarification, but has two intermediate and two final rectangular clarifiers as shown in Fig.1. The excess sludge of the second stage is recycled to the first stage. In case of normal operational conditions the sludge of the first stage is not washed out from this circle. It is properly settling in the middle rectangular clarifier, so the enrichment of the autotrophic nitrifiers is very efficient in the second stage. The sludge of the second stage has similar nitrification capacity as the nitrifying fixed-film (0.3-0.5 kg NH_4^+-N/m^{3}d) [29].

From the first clarifier the excess sludge is pumped to a gravity thickener and from there to the thermophilic hydrolyser. The hydrolyzed sludge is digested at mezophilic temperature. The biogas is stored in a gasholder and reused for heating the hydrolyser and the digester. The daily wastewater production is around 10,000-11,000 m^3 with influent parameters of the Hungarian average (COD 1500 g/m^3, BOD_5 750 g/m^3, NH_4-N 70 g/m^3, 85 TN g/m^3 TSS 1000 g/m^3).

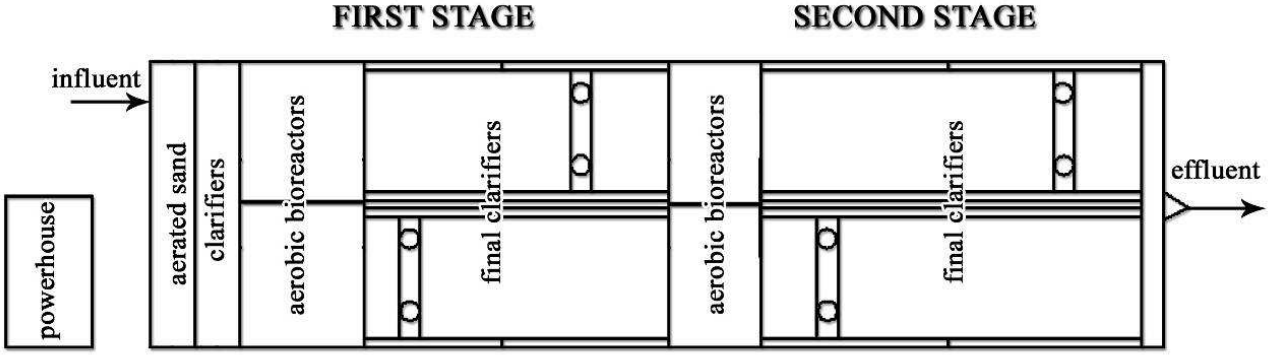

Fig. 1. Scheme of the WWTP of Hódmezővásárhely (Hungary)

4.2. The pilot plant

A pilot scale plant was established to treat a part of the reject water of the digested sludge. The reject water is led from the spin dryer to a reservoir of 1.5m^3 volume with a spillway. The excess reject water flows to the local drainage of the AS plant. The reject water is fed into a moving bed bioreactor with a volume of 2.3m^3 at a rate of 0.1 m^3/h. The hydraulic retention time is around one day. The volume of the carriers is about 0.7m^3, resulting a filling grade of 30%. The actuation is achieved by coarse bubble aeration. The air flow is around 125m^3/h.

According to measurement results the nitrification performance was around 0.3-0.4 kg/(m^3·d). That is three-four times more than it could be in traditional single stage activated sludge systems. Beside that the same level of denitrification performance could be achieved.

The quality of the influent is followed up by analytical measurements of point samples periodically. In case of the influent temperature, dissolved COD and ammonium-nitrogen is measured while in the reactor dissolved oxygen, nitrate-nitrogen, pH and sludge concentration is measured beside the previously mentioned parameters. These parameters are monitored on-line and by point samples. The effluent data are presumed to be the same as in the reactor.

Sample data showed that the concentration of dissolved COD was 770-3000 g/m^3, ammonium was measured 460-1350 gN/m^3, the temperature varied between 20-30°C. Depending on the quality of the

influent the following data was measured in the reactor: dissolved COD 434-895 g/m^3, NH_4^+ 240-376 gN-m^3, NO_3^- 2-60 gN/m^3, DO 0.2-4.1 gO_2/m^3, pH 6.8-8.1. The sludge concentration varied between 195-1740 g/m^3. Table show the measurement results for the influent and the effluent respectively.

Table 1. Measured values for steady-state simulation

	$COD_{dissolved}$	NH4-N
	g/m^3	g /m^3
2008.03.31	1440	1350
2008.04.07	2552	950
2008.04.15	3000	1090
2008.04.25	1440	550
2008.05.21	1201	995
2008.06.12	1525	1060
Average	**1680**	**999**

Table 2. Measured values for steady-state simulation

	$COD_{dissolved}$	NH4-N	NO3-N	DO	pH
	g/m^3	g /m^3	g /m^3	g/m^3	
2008.03.31	434	260	37	1.8	7.5
2008.04.07	612	280	-	1.0	7.4
2008.04.15	1300	376	2	0.2	7.7
2008.04.25	790	230	-	4.1	7.16
2008.05.21	895	256	60	-	6.8
2008.06.12	870	245	20	0.5	8.1
Average	**700**	**235**	**25**	**1.5**	**7.4**

The DO level was controlled manually this is why concentration above 1 g O_2/m^3 could appear. For one occasion the DO was measured 4.1 g O_2/m^3. Since aeration serves as actuator as well, the intensity of aeration was sometimes raised in order to achieve better stirring in the reactor. The results show that despite of the high oxygen concentration measured the other parameters did not change radically which indicates that most of the processes take place in the layers of the biofilm poor of oxygen.

5. Model development

The established system operates with good performance according to the measured values. Nonetheless the ongoing processes are not clear. The efficiency is thought to be partly due to the biofilm but nitrite formation and denitritation is assumed to take place as well and maybe ANAMMOX, too, despite of the inhibiton reported in [4, 8].

Instead of implementing costly devices to measure nitrite and hydrazine, the authors decided to choose model development to map the ongoing processes in the reactor.

Vast literature can be found on using mathematical models to describe the processes of wastewater treatment plants ([26, 27, 28, 9, 33, 35, 16, 24] just mention a few examples) and defining different control strategies for optimal operation and cost efficiency [5, 6, 7]. It has to be mentioned also that wastewater treatment plants are large nonlinear systems subject to large fluctuations in hydrological and biological load together with uncertainties concerning the composition of the incoming wastewater. Therefore mathematical models of these systems can only show trends with high level of uncertainties. Great deviations of inflow data result over- and underestimation near extremes which is one possible reason why some (for example [30]) find the results of mathematical models questionable.

But since on-line instrumentation raise the operation costs and inflow data still cannot be forecasted wastewater treatment modelling and simulation is still widespread and useful tool in estimating effluent quality.

In determining the processes of the examined system the first step was to find a model appropriate for describing MBBR.

5.1. Zero-dimensional biofilm model for MBBR

There is a vast quantity of literature on biofilm models (see [10] for example) but their application limited. A reason for that is that biofilm models have become more and more complex, dedicating more attention to the micro-environment and structure of the biofilm than to the macro-kinetic behaviour of the biofilm system.

The proposed MBBR model was developed by Plattes et al [26, 27, 28] The model includes attachment of particulates to the biofilm and detachment of biofilm into the bulk liquid. [27] The biofilm growth kinetics are modelled with the activated sludge model no. 1 (ASM1) developed by the IWA task group on mathematical modelling for design and operation of biological wastewater treatment [16]. The model does not incorporate biofilm structure in any form, diffusional mass transport limitations are implemented implicitly by

ASM No.1 and manifest by adapted half-saturation coefficients in the Monod expression of the activated sludge model. [28] Plattes et al studied the OUR responses of the active autotrophic and heterotrophic biomass in the MBBR. The respirograms obtained in the experiment showed analogous behaviour as of activated sludge [26]. The result indicates that mass transport limitations for ammonia nitrogen and readily biodegradable substrate were not more important in the MBBR system than in typical activated sludge systems therefore the proposed model is suitable for simulating the processes that take place in the MBBR. It is important to state that the model was validated for typical municipal wastewater and not for reject water.

5.2. Four-step nitrogen removal

Ni et al. [24] describe two step denitrification processes for ASM No.3. Denitrification was described by [33, 35] for ASM1 previously in three steps including N_2O as intermediate in nitrogen gas formation.

The organic material storage could have been a solution for better fitting of COD results but nitrification processes were not explained at all in either study. Therefore another solution had to be found.

Dosta et al. [9] described a model of sequencing batch reactor treating reject water with two step nitrification and denitrification. The concept was applied with modifications. One important difference is that the authors did not take the inhibition factors into consideration.

Nitrification is defined as a two-step process, where ammonium is firstly oxidized to nitrite (nitritation, Eq. (3)) and subsequently nitrite is oxidized to nitrate (nitratation, Eq. (4)).

$$NH_4^+ + \tfrac{3}{2}O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

(Ammonium oxidizing biomass) (3)

$$NO_2^- + \tfrac{1}{2}O_2 \rightarrow NO_3^-$$

(Nitrite oxidizing bacteria) (4)

Denitrification is then described as the reduction of NO_3^- into NO_2^- (Eq. (5)) and further on to N_2 (Eq. (6)) by the catabolism of heterotrophic bacteria. This process is carried out under anoxic conditions and with a biodegradable carbon source, such as acetate, as electron donor. [9]

$$4NO_3^- + C_2H_4O_2 \rightarrow 4NO_2^- + 2CO_2 + H_2O \quad (5)$$

$$8NO_2^- + 3C_2H_4O_2 + H_2O \rightarrow 4N_2 + 8OH^- + 6CO_2 \quad (6)$$

The previously set up model was modified so that autotrophic biomass was divided into ammonia and nitrite oxidizing bacteria and the two denitrification processes were added as well. The processes and the kinetic parameters were adopted from Dosta et al. [9] with the exception that inhibition terms were not added.

5.3. Inhibition terms

Anthonisen et al. [2] investigated the range of inhibiting concentrations of nitrification. In their work three inhibition zones are defined, first the inhibition of nitrite oxidising organisms (Nitrobacter) by unionised ammonia (NH_3>0.1-1.0 g/m^3), second the inhibition of ammonia oxidising bacteria (Nitrosomonas) by unionised ammonia (NH_3>10-150 g/m^3) and third the inhibition of Nitrobacter by nitrous acid (HNO_2>0.2-2.8 g/m^3). Anthonisen points out that acclimation and temperature beside other parameters may affect the inhibitory concentrations.

In order to define the inhibition factors that can be directly related to the model state variables the following equations were used [17].

$$K_{TNO2} = \frac{K_{HNO2} \cdot (K_a \cdot 10^{pH} + 1) \cdot 14}{47} \quad (7)$$

$$K_{TA} = \frac{K_{FA} \cdot \left(K_b / K_w + 10^{pH}\right) \cdot 14}{10^{pH} \cdot 17} \quad (8)$$

Where

K_{TNO2} is the inhibition coefficient for total nitrite and nitrous acid nitrogen (g N/m^3),

K_{TA} is the inhibition coefficient for total ammonia and ammonium nitrogen (g N/m^3),

K_{HNO2} is the inhibition coefficient for free nitrous acid (g/m^3),

K_{FA} is the inhibition coefficient for free ammonia (g/m^3),

pH is the average of the measured pH values: 7.4.

$$K_a = \exp\left(\frac{-2300}{273+T}\right) \quad (9)$$

$$K_b / K_w = \exp\left(\frac{6344}{273+T}\right) \quad (10)$$

Where
K_a is the ionisation constant of nitrous acid equilibrium,
K_b is the ionisation constant of ammonia equilibrium,
K_w is the ionisation constant of water and
T is the average temperature taken as 22°C.

K_{HNO2} and K_{FA} were determined in accordance with Anthonisen et al [2]. For Nitrobacter K_{HNO2} was 0.2-2.8 g/m^3 and K_{FA_NO} 0.1-1 g/m^3 while the inhibitor coefficient concerning Nitrosomonas (K_{FA_AO}) was 10-150 g/m_3.
Another version of calculation for percentage of free ammonia can be found in [34].

5.4. Processes of ANAMMOX bacteria

Hao [14] in his thesis described the mathematical model of CANON (Completely Autotrophic Nitrogen removal Over Nitrite). That included the description of nitritation, nitratation and anaerobic ammonium oxidation. The results on defining the kinetic expressions of ANAMMOX activity was applied to the model of the present study.
The growth process of ANAMMOX organisms were added according to [14] while the decay rate was described by a first order expression with respect to the biomass (biofilm) concentration as was described in [16].

6. Results and discussion

The model development was done using MATLAB/Simulink R2007b program package. The program package offers the utilization of graphical interfaces beside the freedom of creating codes in several languages [22, 21]. The combination of these features makes the MATLAB/Simulink environment favourable among researchers from other fields than computer science (see for example [13]).
The different versions of the model of the biological reactor and the supplementary elements were implemented in with the help of s-functions written in C language [21, 22].
Steady state simulation was performed first with default parameters then with modifications in order to fit experimental data. Table 1 and 2 show the influent and effluent data respectively. Steady-state simulations were carried out with the averages derived from the influent parameters. Results were compared to the averages values of Table 2. Since the influent concentrations varied to a great extent simulation with minimum and maximum ammonia concentrations were carried out after calibrating the model to average concentrations in order to see how the model can treat such great deviations. Unfortunately the results are far from satisfactory (see Table 3 to 7).

The first session proved to be inadequate to describe simultaneous nitrification and denitrification processes. Ammonia could be fully removed from the system but denitrification in that case did not take place at all according to the received values.
Therefore nitrogen removal via nitrite was implemented in the model for suspended biomass and biofilm, too. The results of session 2 are shown in Table 3. The mass transfer coefficient for aeration (K_LA) was determined to be 27 1/d for the following sessions.

Table 3. Comparison of simulated and measured data: *Session 2* – without inhibition

	$COD_{diss.}$	NH_4-N	NO_3-N	NO_2-N	N_2	DO
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3
Average (999 g/m^3 NH4-N)						
Simulated	360	220	21	301	518	0.02
Measured	700	235	25	n.a.	n.a.	1.5
At maximum NH_4-N (1350 g/m^3)						
Simulated	278	388	32	533	421	0.02
Measured	434	260	37	n.a.	n.a.	1.8
At minimum NH_4-N (550 g/m^3)						
Simulated	279	0.8	319	3	284	0.07
Measured	790	230	n.a	n.a	n.a	4.1

The results for ammonia and nitrate were near to the measured data. Nonetheless the developed model could not produce the same results for the other examined components.
The received COD value was solely the amount of inert soluble organic material that was estimated at the stage of influent characterization. That means that all accessible biodegradable substrate was consumed according to the model, which was not true to the real system. Though nitrite and nitrogen gas was not measured, simulation results show that a considerable amount of nitrite accumulates in the modelled system.
The following step was to introduce the inhibition terms into the model. It is important to state that in these cases other model parameters were not adjusted.
Two sessions were carried out with different inhibition coefficients. These factors were calculated with Eqs (7) and (8). Session 3 was carried out with the maximum values given by Anthonisen et al [2] while in Session 4 the minimum values for inhibition terms were used.

Both simulations gave very similar results (see Table 4 and 5). The only difference could be observed in cases of nitrate concentrations. That is due to the inhibition effect of free ammonia on nitrite oxidising organisms which was taken between 0.1-1 g/m^3 free ammonia (7.2-72.5 g/m^3 projected to total ammonium).

Table 4. Comparison of simulated and measured data: *Session 3* – with inhibition coefficients K_{AO_TA}=10871 g/m^3; K_{NO_TA}=72.5 g/m^3 and K_{TNO2}=8614 g/m^3.

	$COD_{diss.}$	NH_4-N	NO_3-N	NO_2-N	N_2	DO
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3
Average (999 g/m^3 NH4-N)						
Simulated	360	205	0	321	532	0.02
Measured	700	235	25	n.a.	n.a.	1.5
At maximum NH_4-N (1350 g/m^3)						
Simulated	278	369	0	569	436	0.02
Measured	434	260	37	n.a.	n.a.	1.8
At minimum NH_4-N (550 g/m^3)						
Simulated	278	0.3	0	455	154	0.29
Measured	790	230	n.a	n.a	n.a	4.1

Table 5. Comparison of simulated and measured data: *Session 4* – with inhibition coefficients K_{AO_TA}= 724.7 g/m^3; K_{NO_TA}=7.2 g/m^3 and K_{TNO2}=615.3 g/m^3.

	$COD_{diss.}$	NH_4-N	NO_3-N	NO_2-N	N_2	DO
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3
Average (999 g/m^3 NH4-N)						
Simulated	360	223	0	334	504	0.03
Measured	700	235	25	n.a.	n.a.	1.5
At maximum NH_4-N (1350 g/m^3)						
Simulated	278	396	0	587	391	0.04
Measured	434	260	37	n.a.	n.a.	1.8
At minimum NH_4-N (550 g/m^3)						
Simulated	279	0.3	0	455	153	0.29
Measured	790	230	n.a	n.a	n.a	4.1

The comparing values of inhibition coefficients and measurements showed great similarities. The results also indicate that some processes are missing while others do not take place to the extent that was suggested by the calculation.

The great difference between measured and simulated dissolved COD concentrations may occur from two causes. One is that the ratio of inert and biodegradable soluble organic material was not correctly set. The other reason may be that it indicates that other processes – presumably ANAMMOX – take place. The high concentration of nitrite simulated seemed to justify that to. This would be contradictory to the results of Chamchoi et al. [4] (cf. Section 2.) but it is assumed that the special structure of the moving bed bioreactor allows the simultaneous operation of ANAMMOX and denitrifying bacteria to a certain extent. The two explanations are not contradictory.

The great difference of measured and calculated DO is possibly due to the complexity of the MBBR system. DO was measured in the bulk liquid while the simulated oxygen concentration refers to the whole volume reactor including the deeper layers of biofilm where oxygen is not present. From this point of view the present model has to be improved in order to reduce the huge differences between measured and simulated DO concentration.

Since little progress could be achieved by introducing inhibition terms to the model further steps had to taken. New processes of ANAMMOX activity were added. In Session 5 was carried K_LA, and several kinetic parameters had to be altered in order to reach the desired values.

Because measurement data showed that there was a considerable amount of nitrate in the reactor, the inhibition coefficient of total ammonium for nitrite oxidising bacteria was changed to 261 g/m^3 which is equivalent to 3.6 g/m^3 of free ammonia according to Eq(8). Some other model parameters were also altered, especially those that are related to heterotrophy bacteria in order to reduce the performance of heterotrophic denitrification.

Table 6. Comparison of simulated and measured data: *Session 5* – ANAMMOX processes introduced (K_{AO_TA}=10871 g/m^3; K_{NO_TA}=261 g/m^3 and K_{TNO2}=8614 g/m^3).

	$COD_{diss.}$	NH_4-N	NO_3-N	NO_2-N	N_2	DO
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3
Average (999 g/m^3 NH4-N)						
Simulated	360	214	25	73	787	0.05
Measured	700	235	25	n.a.	n.a.	1.5
At maximum NH_4-N (1350 g/m^3)						
Simulated	279	359	31	279	736	0.05
Measured	434	260	37	n.a.	n.a.	1.8
At minimum NH_4-N (550 g/m^3)						
Simulated	279	3.34	234	1.3	398	0.08
Measured	790	230	n.a	n.a	n.a	4.1

From Table 6 it is obvious that there is no change in the values of dissolved COD. That was at first surprising. But since there is little information on the composition of the reject water, it was assumed that the inert fraction is only 20% of the dissolved COD based on a single measurement of inorganic and organic fractions of the liquid phase. This assumption proved to be wrong.

In case of dinitrogen gas formation from nitrite showed better results. The nitrite concentration was below 100 g/m^3. That is in agreement with the results of Hao [14].

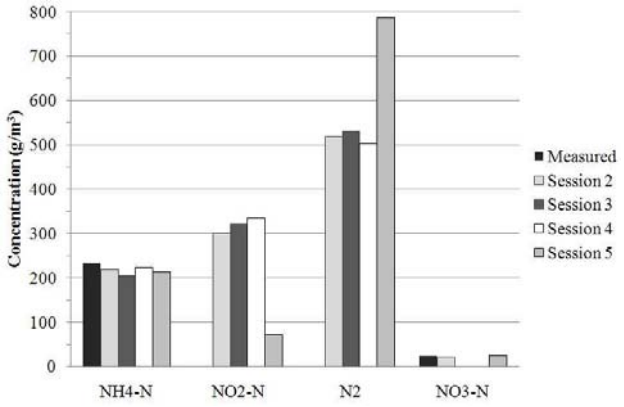

Fig. 1. Comparison of nitrogen forms of the different modelling process sessions

It is important to state that the oxygen concentration could not be raised in the simulation but in Session 5 K_LA was one-tenth of the values that were used in the previous sessions (3.1 1/h versus 30 1/h).

After understanding that the characterisation of the influent might be incorrect further steady-state simulations are being carried out at present. Results are promising but calibration needs to be done first.

7. Conclusions

According to measurement results implementing an aerated moving bed bioreactor of 2.3 m^3 volume for treating reject water 0.3-0.4 kg/(m^3·d) nitrification performance could be achieved. That is three-four times more than it could be in traditional single stage activated sludge systems. Beside that the denitrification performance was at the same level.

In the near past based on the experience of the operation of eight months the following changes have been carried out:

- The buffer tank was replaced by a basin of 5 m^3 volume in order to assure stable influent quality.
- Measurement and monitoring system was improved. An ammonium probe was implemented in the buffer tank to monitor the influent.

After two months of stable operation after the alteration the system could perform 0.7-0.9 kg/(m^3·d) nitrification and 0.6-0.8 kg/(m^3·d) efficiency. With this nitrogen removal rate a decrease of around 10% in nitrogen load could be achieved on the main line in case of implementing a full-scale MBBR hybrid system.

Since the pilot-scale plant showed such good performance further studies on possible controlling strategies are planned. On-line monitoring devices are applied to gather sufficient data for dynamic simulations to be carried out in the future.

Concerning modelling processes the following conclusions were drawn:

- The proposed 0D biofilm model is a good basis for describing the processes in MBBR designed for treating reject water.
- Nitrogen removal is assumed to go over nitrite according to the model.
- Comparing simulated and measured data it is assumed the ANAMMOX process takes place as well.
- Influent characterisation is crucial concerning the goodness of the model especially concerning special wastewaters when literature data are not applicable.
- The problem of COD and DO has to be solved before using the model for other purposes.

Further research is planned on implementing temperature dependency of parameters in the model. Beside that respirometric analysis is needed to estimate kinetic parameters of the model in order to improve accuracy of simulation. Repetitive measurements have to be carried out to understand the composition of the influent before further simulations.

It can be stated that though the model of MBBR needs corrections and validation on full-scale plants but model development can help to understand the processes that are ongoing in a reactor.

References

[1] Ahn, Y-H., Sustainable nitrogen elimination biotechnologies: A review, *Process Biochemistry* Vol. 41, No.8, 2006, pp. 1709–1721.

[2] Anthonisen, A.C., Loehr, R.C., Prakasam, T.B.S., Srinath, E.G., Inhibition of nitrification by ammonia and nitrous acid. *Journal - Water Pollution Control Federation*, 48, 1976, 835–852.

[3] Brouwer, M., van Loosdrecht, M. C. M., Heijnen, J.J., *One reactor system for ammonium removal via nitrite. STOWA Report,*

96-01. Utrecht (The Netherlands): STOWA, 1996 (ISBN 90 74476 55 4).

[4] Chamchoi, N., Nitisoravut, S., Schmidt, J. E., Inactivation of ANAMMOX communities under concurrent operation of anaerobic ammonium oxidation (ANAMMOX) and denitrification, *Bioresource Technology* Vol. 99, No. 9, 2008, pp. 3331–3336.

[5] Clara, N., Neural Networks complemented with Genetic Algorithms and Fuzzy Systems for Predicting Nitrogenous Effluent Variables in Wastewater Treatment Plants, *WSEAS Transactions on Systems*, 2008, Vol. 7, No. 6, pp. 695-705.

[6] Copp, J. B. (Ed.), The COST Simulation Benchmark: Description and Simulator Manual (a product of COST Action 624 & COST Action 682), Luxembourg: Office for Official Publications of the European Communities online edition (2002)

[7] COST 682/624 Action website (www.ensic.u-nancy.fr/COSTWWTP) – The European Co-operation in the field of Scientific and Technical Research. Access: 3.11.2008.

[8] Dong, X., Tollner, E. W., Evaluation of Anammox and denitrification during anaerobic digestion of poultry manure, *Bioresource Technology* Vol. 86, No. 2, 2003, pp. 139–145.

[9] Dosta, J., Galí, A., Benabdallah El-Hadj, T., Macé, S., Mata-Álvarez, J., Operation and model description of a sequencing batch reactor treating reject water for biological nitrogen removal via nitrite *Bioresource Technology* Vol. 98, No. 11, 2007, pp. 2065–2075.

[10] Eberl, H., Morgenroth, E., Noguera, D., Picioreanu, C., Rittmann, B., van Loosdrecht, M., Wanner, O., *Mathematical modelling of biofilms Scientific and Technical Report No.18.* IWA Publishing London, 2006.

[11] Fux, C., Biological nitrogen elimination of ammonium-rich sludge digester liquids, *Thesis*, 2003, e-collection.ethbib.ethz.ch/eserv/eth:26566/eth-26566-02.pdf 12.11.2008.

[12] Fux, C., Boehler, M., Huber, P., Brunner, I., Siegrist H., Biological treatment of ammonium-rich wastewater by partial nitritation and subsequent anaerobic ammonium oxidation (anammox) in a pilot plant, *Journal of Biotechnology* Vol. 99, No. 3, 2002, pp. 295-306.

[13] Galvanauskas, V., Simutis R., Software tool for efficient hybrid model-based design of biochemical processes, *WSEAS Transactions on Biology and Biomedicine*, 2007, Vol. 4, No. 9, pp. 136-144.

[14] Hao, X. D., Model-based optimisation of sustainable biological nutrient removal processes, *Thesis*, 2001, www.library.tudelft.nl/ws/search/publications/search/metadata/index.htm?docname=084918 (10.11.2008.)

[15] Hellinga, C., Schellen, A. A. J. C., Mulder, J. W., van Loosdrecht, M. C. M., Heijnen. J. J., The SHARON process: an innovative method for nitrogen removal from ammonium rich wastewater, *Water Science and Technology*, Vol. 37, No. 9. 1998, pp. 135-142.

[16] Henze, M., Grady, C. P. L., Gujer, W., Marais, G. v. R., Matsuo, T.: *Activated Sludge Model No.1. IAWPRC Scientific and Technical Report No.1.*, IAWPRC, London, U.K., 1987.

[17] Jubany, I., Carrera, J., Lafuente, J., Baeza, J. A., Start-up of a nitrification system with automatic control to treat highly concentrated ammonium wastewater: Experimental results and modelling *Chemical Engineering Journal* Vol. 144 No. 3, 2008, pp. 407–419

[18] Kampschreur, M. J., van der Star, W. R. L., Wielders, H. A., Mulder, J. W., Jetten, M. S. M., van Loosdrecht, M. C. M., Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment *Water Research* Vol. 42, No. 3, 2008, pp. 812- 826

[19] Khin, T., Annachhatre, A.P., Novel microbial nitrogen removal processes *Biotechnology Advances* Vol. 22, No. 7, 2004, pp. 519–532

[20] Krhutkova, O., Novak, L., Pachmanova, L., Benakova, A., Wanner, J., Kos, M., In situ bioaugmentation of nitrification in the regeneration zone: practical application and experiences at full-scale plants, *Water Science and Technology* Vol. 53, No. 12, 2006, pp. 39-46.

[21] Martínez, J. C.: *Benchmarking the STAR Controller using Matlab*. MSc. dipl., 2006, Lund, Sweden, pp.101-110,

[22] MathWorks: Simulink® 7 Writing S-Functions. *Online Edition*, The MathWorks, Inc., Natick, Massachusetts, USA. 2007

[23] Mulder, J.W., van Loosdrecht, M.C.M., Hellinga, C., van Kempen, R., Full-scale application of the SHARON process for treatment of rejection water of digested sludge dewatering, *Water Science and Technology* Vol. 43, No. 11, 2001. pp. 127–134.

[24] Ni, B-J., Yu H-Q., An approach for modeling two-step denitrification in activated sludge

systems, *Chemical Engineering Science*, Vol. 63, No. 6, 2008, pp. 1449-1459

[25] Ødegaard, H. , Rusten, B., Westrum, T., A New Moving Bed Biofilm Reactor – Application and Results, *Water Science and Technology*, Vol. 29. No. 11, 1994, pp. 157-165.

[26] Plattes, M., Fiorelli, D., Gillé, S., Girard, C., Henry, E., Minette, F., O'Nagy, O., Schosseler, P.M., Modelling and dynamic simulation of a moving bed bioreactor using respirometry for the estimation of kinetic parameters *Biochemical Engineering Journal* Vol. 33, No. 3, 2007, pp. 253-259.

[27] Plattes, M., Henry, E., Schosseler, P.M., A zero-dimensional biofilm model for dynamic simulation of moving bed bioreactor systems: Model concepts, Peterson matrix, and application to a pilot-scale plant *Biochemical Engineering Journal* Vol. 40, No. 2, 2008, pp. 392–398.

[28] Plattes, M., Henry, E., Schosseler, P.M., Weidenhaupt, A., Modelling and dynamic simulation of a moving bed bioreactor for the treatment of municipal wastewater *Biochemical Engineering Journal* Vol. 32, No. 2, 2006, pp. 61–68.

[29] Pulai, J., Kárpáti Á., Hungarian data and knowledge in the field of two stage activated sludge systems, *Teaching Aid, 10th book*, University of Pannonia, Veszprém, Hungary, 2004, pp. 48-55.

[30] Skrjanc, I., Monitoring of Waste-water Treatment Plant Based on Fuzzy Model, *WSEAS Transactions on Systems*, Vol. 6; No. 3, 2007,pp. 637-642.

[31] Strous, M., Heijnen, J.J., Kuenen, J.G., Jetten, M.S.M., The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidizing micro-organisms, *Applied Microbiology and Biotechnology* Vol. 50, No. 5., 1998, pp. 589-596.

[32] Sumino, T., Isaka, K., Ikuta, H., Saiki, Y., Yokota, T., Nitrogen removal from wastewater using simultaneous nitrate reduction and anaerobic ammonium oxidation in single reactor, *Journal of Bioscience and Bioengineering*, Vol. 102, No. 4, 2006, pp. 346-351.

[33] von Schulthess, R., Wild, D., Gujer, W., Nitric and Nitrous Oxides from Denitrifying Activated Sludge at Low Oxygen Concentration *Water Science and Technology* Vol. 30, No. 6, 1994, pp. 123-132.

[34] Wett, B., Rauch, W., The role of inorganic carbon limitation in biological nitrogen removal of extremely ammonia concentrated wastewater, *Water Research,* Vol. 37 No. 5, 2003, pp. 1100–1110

[35] Wild, D., von Schulthess, R., Gujer, W., Synthesis of denitrification enzymes in activated sludge: modelling with structured biomass *Water Science and Technology* Vol. 30, No. 6, 1994, pp. 113-122.