Model development for determining 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 [17] was chosen. Simulation data in the study of Plattes et al. [18] 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. Further research is planned to prove this hypothesis.

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

1. Introduction
Reject water flows originating from sludge treatment have a high ammonium content (typically 500–1500 g N/m³), 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 [11]. 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) [9, 13] and nitrification combined with augmentation of the main treatment line. Opposed to augmentation the reject water can be treated separately with the combination of SHARON-ANAMMOX processes [12] 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.

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. [9] – 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.

\[ NH_4^+ + HCO_3^- + 0.75O_2 \rightarrow \]
\[ \rightarrow 0.5NH_3 + 0.5NO_2^- + CO_2 + 1.5H_2O \]

(1)

The ANAMMOX organisms grow with CO₂ as the sole carbon source and uses nitrite as the electron donor to produce cell material [1]. Strous et al. [20] gives the stoichiometry of anaerobic ammonium oxidation as:

\[ NH_4^+ + 3.2NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow \]
\[ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.066CH_2O_{0.15} + 2.03H_2O \]

As shown in Eq.(2) nitrite must first be produced up to a nitrite/ammonium ratio of about 1.3 [8]. ANAMMOX activity was suppressed when COD (dissolved) concentration was over 300 g/m³ [4]. Competition between ANAMMOX and denitrifying communities was reported earlier by other researchers [4, 5]. Confirmation was made through a detection of hydrazine, which is a unique intermediate of ANAMMOX activity, and FISH (fluorescence in situ hybridization) test [4].

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 [15]. 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 [15]. 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 $^{-1}$) [19]. 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)](image-url)
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 1.5 m³ 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 2.3 m³ at a rate of 0.1 m³/h. The hydraulic retention time is around one day. The volume of the carriers is about 0.7 m³, resulting a filling grade of 30%. The actuation is achieved by coarse bubble aeration. The air flow is around 125 m³/h. 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/m³, ammonium was measured 460-1350 gN/m³, 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/m³, NH₄⁺ 240-376 gN-m³, NO₃⁻ 20-60 gN/m³, DO 0.2-1.8 gO₂/m³, pH 6.8-8.1. The sludge concentration varied between 195-1740 g/m³. The DO level was controlled manually this is why concentration above 1 g O₂/m³ could appear occasionally.

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 inhibition reported in [4, 5].

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. 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 [7] 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 [16, 17, 18] The model includes attachment of particulates to the biofilm and detachment of biofilm into the bulk liquid. [17] 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 [10]. 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. [18] 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 [16]. 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. [14] describe two step denitrification processes for ASM No.3. Denitrification was described by [21, 22] for ASM1 previously in three steps including N₂O 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. [6] 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 (nitrification, Eq. (3)) and subsequently nitrite is oxidized to nitrate (nitratation, Eq. (4)).

\[
\text{NH}_4^+ + \frac{3}{2}O_2 \rightarrow \text{NO}_2^- + 2H^+ + H_2O
\]

(Ammonium oxidizing biomass) \hspace{1cm} (3)

\[
\text{NO}_2^- + \frac{1}{4}O_2 \rightarrow \text{NO}_3^-
\]

(Nitrite oxidizing bacteria) \hspace{1cm} (4)

Denitrification is then described as the reduction of NO₃⁻ into NO₂⁻ (Eq. (5)) and further on to N₂ (Eq. (6)) by the catabolism of heterotrophic bacteria. This process is carried out under anoxic conditions and with a
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. [6] with the exception that inhibition terms were not added.

### 6. Results and discussion

Steady state simulation was performed first with default parameters then with modifications in order to fit experimental data. Table 1 shows the influent and effluent data to which the simulation results were compared to.

<table>
<thead>
<tr>
<th></th>
<th>COD_dissed</th>
<th>NH₄-N</th>
<th>NO₂-N</th>
<th>NO₃-N</th>
<th>DO</th>
<th>pH</th>
<th>Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>1440</td>
<td>1350</td>
<td>-</td>
<td>-</td>
<td>7.5</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Effluent</td>
<td>434</td>
<td>260</td>
<td>37</td>
<td>0.5</td>
<td>7.1</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

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 following results (Table 2) had been achieved after slight modification of parameters such as maximum growth of ammonia and nitrite oxidizing bacteria.

<table>
<thead>
<tr>
<th></th>
<th>COD_diss</th>
<th>NH₄-N</th>
<th>NO₂-N</th>
<th>NO₃-N</th>
<th>N₂</th>
<th>DO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent</td>
<td>343</td>
<td>260</td>
<td>37</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The results for ammonia and nitrate showed 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 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 indicate that a considerable amount of nitrite would accumulate in the modelled system. This is contradictory to the results of Anthonisen et al. [2] in which it was stated that nitration is inhibited by free HNO₂ of 2.8 mg/l concentration which would result low pH. Measurement results show that this does not happen in the pilot plant. That indicates that the inhibition factors omitted in the course of model development should be applied to the process. This also means that other processes do not take place to the extent that was suggested by the calculation.

Further research is planned on implementing ANAMMOX process and 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.

### 7. Conclusions

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.

### References

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