

Cycle time determination and process control of Sequencing Batch Membrane Bioreactors

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Abstract In this paper a method to determine the cycle time for Sequencing Batch Membrane Bioreactors (SBMBRs) is introduced. One of the advantages of Sequencing Batch Membrane Bioreactors is the simplicity of adapting them to varying wastewater composition. The benefit of this flexibility can only be fully utilised if the cycle times are optimised for the specific inlet load conditions. This requires either proactive and ongoing operator adjustment or active predictive instrument based control. Determination of the cycle times for conventional SBR plants is usually based on historic experience. Due to the higher MLSS concentrations in SBMBRs and the limited experience with their application, a new approach to calculate the cycle time had to be developed. Based on results from a semi-technical pilot plant, the paper presents an approach for calculating the cycle time in relation to the influent concentration according to ASM 1 and the German HSG Approach. The approach presented in this paper considers the increased solid contents in the reactor and the resultant shortened reaction times. This allows for an exact calculation of the nitrification and denitrification cycles with a tolerance of only a few minutes. Ultimately the same approach can be used for a predictive control strategy and for conventional SBR plants.

Keywords SBR, membrane bioreactor, SBMBR, cycle time, process control

1 INTRODUCTION

Sequencing Batch Membrane Bioreactors typically use sequenced filling and discharge cycles operated in a membrane bioreactor. This is regardless of the fact that the membranes can be installed in the Sequencing Batch Reactor or in a separate reactor and shared between different SBRs. In regard to the membrane bioreactor the advantages of the sequencing batch cycle is the improved denitrification performance and the improved sludge quality due to the initially higher organic loading compared to continuous flow plants. This improves the membrane performance as it is widely accepted that the sludge quality e.g. measured as sludge volume index (SVI) is a good indicator for the filterability of the sludge (e.g. Meng and Yang, 2007). In regard to the sequencing batch reactor technology the use of membranes has the advantage of a reduced cycle time as a result of the elimination of the settling phase as well as the reduced reactor volume due to the higher mixed liquor suspended solids (MLSS) concentration possible when using membranes for the sludge separation process. These and other advantages have led to an increased interest in the Sequencing Batch Membrane Bioreactor technology over the last decade. Sequencing Batch Membrane Bioreactors have been used for the treatment of greywater (Scheumann and Kraume, 2008 and Kraume et al., 2010), municipal wastewater (Krampe and Krauth, 2001, Huggins et al., 2009, Serrano et al., 2011 and Laera et al., 2011) and industrial wastewater (Martinez et al., 2003, Bae et al., 2003, Vargas et al., 2008 and Shariati et al., 2011).

The downside of the combination of the SBR and Membrane Bioreactor technologies is the risk of increased membrane fouling which has been widely reported by several authors (Defrance and Jaffrin, 1999, Shin and Kang, 2002, Kang et al., 2003, McAdam et al., 2005, Vargas et al., 2008, Scheumann and Kraume, 2008, Tu et al., 2010, Xi et al., 2011, Shariati et al., 2011). Laera et al. (2011) conclude that SBMBR systems offer a great flexibility and that the operator can easily manage to obtain the

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desired effluent quality with negligible effects on biomass yield and filtration performance. Kraume et al. (2010) found that in the case of space limitation like e.g. in hotels, the small footprint of the SBMBR can outweigh the inconveniences of potentially required higher membrane surface as a result of increased fouling. Pressl et al. (2010) successfully tested a small 15 PE SBMBR system for applications with increased requirements for surety of pathogen removal and achieved stable operation with excellent performance. Based on the available literature, the performance of the membranes was not focus of this research.

The next step towards a broader implementation of the SBMBR technology is to provide more clarity in regard to the design and layout. Apart from the hydraulic capacity of the plant, the determination of the cycle times for the biological processes is very important. If the cycle times are too long, the available volume is not utilised efficient, if the cycle times are too short, the effluent targets cannot be achieved. Usually the cycle times are assumed based on experience but these experiences are currently not available for SBMBR systems. The overall focus of this research was the improvement of the denitrification performance of MBRs by means of a sequencing batch cycle. Aim of this study was to determine the required cycle times for SBMBR applications and develop a method to predict the required cycle times for new plants. Another aim was to demonstrate the benefit of advanced cycle time control in regard to improved capacity and effluent quality for SBMBR plants. The key findings of the study are summarised in this paper based on the operation of a pilot plant in municipal wastewater.

2 DESCRIPTION OF THE PILOT PLANT AND TEST

The pilot plant consisted of a reactor with a volume of 3.16 m³ at top water level and 1.58 m³ at bottom water level, thus allowing for a maximum volume exchange ratio (VER) = 0.5. A stirrer was installed above the submerged membranes. All installations, including the membranes, could be pulled out of the reactor for cleaning. The plant was fed with pre-treated municipal wastewater from the Teaching and Research Sewage Treatment Plant of Stuttgart University. The average BOD₅/COD ratio of the sewage is 0.65 and for the purpose of this study only the COD was analysed and converted into BOD₅ using the above ratio where required for calculations. The average results for the different periods are summarised in Table 1 and 2.

The membranes were hollow fibre membranes with a pore size of 0.1 µm from Mitsubishi Rayon Co., LTD company in Tokyo, Japan. The membranes were configured in a module with a total membrane area of 64 m² (manufacturer's information). During the filtration cycles the membranes were operated at a constant net flux of 10 L/m²/h. The filtration cycles were set to 10 minutes with 8 min filtration and 2 min pause. No permeate backwash was trialed during the trials.

On-line measuring equipment for ammonia and nitrate was installed in a bypass package which included pre-filtration by Kubota plate membranes. The intake to the plate membranes were installed in the downstream area of the pilot plant at the level of the hollow fibre module. This arrangement always guaranteed sufficient overflow of the membranes. A pump served to produce the necessary negative pressure. The settings remained constant during the entire test period with the time to convey the samples from the reactor to the analyser being approximately 10 minutes. The NH₄-N concentration was measured using a Hach-Lange AMTAXinter Analyser and NO_x-N was measured using a Hach-Lange NITRATAX Analyser.

The investigations were divided into three test periods. In the first period, the plant was operated with constant reaction times. In the second period, the duration of the reaction times was controlled by the

ammonium and nitrate concentrations in the reactor. In the last test period, the influent composition and the solids contents in the reactor were purposefully varied. The pilot plant was dynamically simulated in parallel, on the basis of the ASM 1 (Gujer et al., 1987) using the software package Simba 3.4+ (ifak, 1998).

3 RESULTS AND DISCUSSION

3.1 Membrane performance

As mentioned before, the net flux during filtration was fixed to 10 L/m²/h for the purpose of this trial after a short start-up phase. With constant flux the transmembrane pressure increased over time, once a transmembrane pressure of 0.25 bar was reached the membranes were chemically cleaned with sodium hypochlorite and caustic soda. The performance of the membranes is summarised in Figure 1.

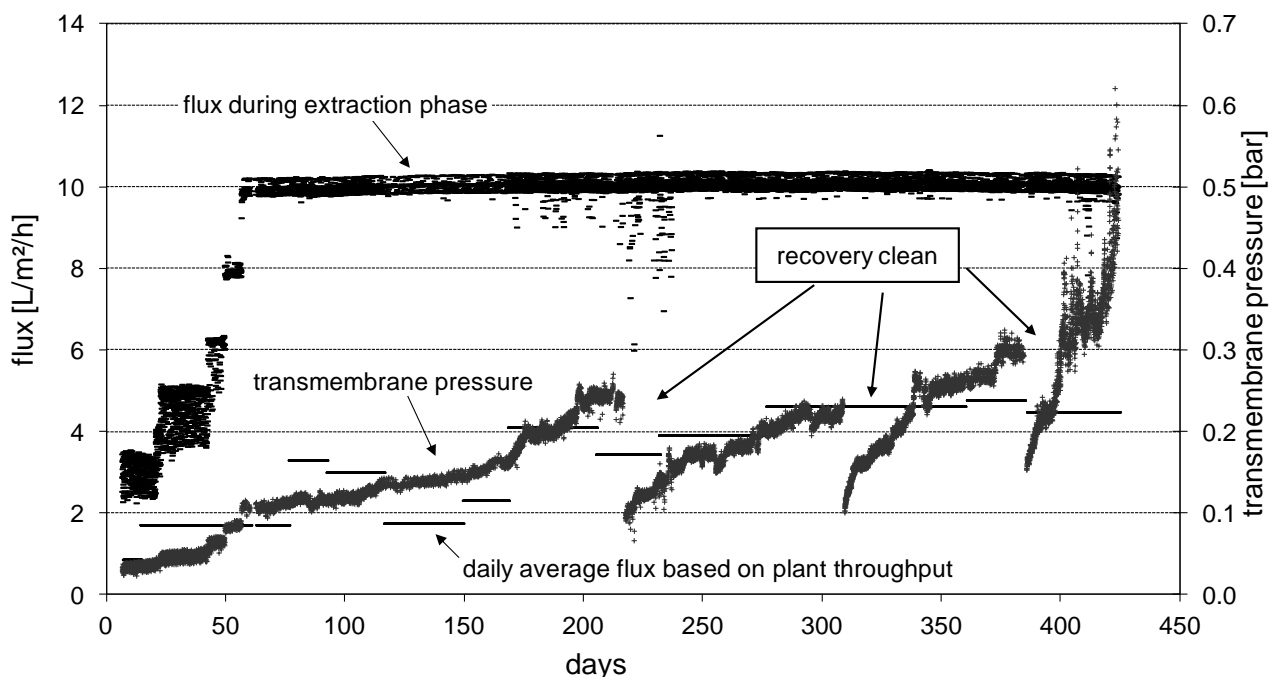


Figure 1: Membrane flux and transmembrane pressure over the trial period

In addition to the flux during the extraction phase, the daily average flux calculated based on the daily throughput is presented. The increased plant throughput during the phases with controlled cycle times can be seen as the reason for the faster increase of the transmembrane pressure in the second half of the study. As the purpose of the trials was to optimise the nitrogen removal performance of SBMBRs the hydraulic performance of the membranes was not optimised.

3.2 Tests with constant cycle time

In the first test with the exchange ratios 0.1, 0.2 and 0.3 the duration of the denitrification phase (mixing) and the nitrification phase (aeration without permeate extraction) for each exchange ratio was fixed. The following objectives were pursued in this section:

- Testing a simple system with fixed cycle times, particularly with a focus on small wastewater treatment systems.
- Gathering of experiences with the online system and appropriate control variables for the automation of the cycle times.

The key operational data are summarised in Table 1. As expected the nitrogen removal efficiency dropped with increased VER while the capacity increased.

Table 1: Extract of results with fixed cycle times (average values)

Exchange ratio [-]	VER = 0.1	VER = 0.2	VER = 0.3
Q _d [m ³ /d]	3.55	5.02	6.34
COD [mg/L]	384	355	393
SS [mg/L]	170	163	150
TKN [mg/L]	57.5	44.2	60.8
P _{tot} [mg/L]	6.9	6.5	7.8
MLSS [g/L]	15.6	12.7	11.7
BOD ₅ sludge loading rate [kg BOD ₅ /kg MLSS/d]	0.032	0.046	0.061
SRT [days]	58	49	26
t _{fill} [min]	9	16	27
t _{mix} [min]	30	29	25
t _{aerate} [min]*	30	47	42
t _{extract} [min]	15	36	62
N _{inorg,eff} [mg/L]	7.8	8.3	19.2
η _{DN} [%]	83.2	70.7	59.9

* only considering aeration without permeate extraction

3.2 Test with variable cycle time

The same exchange ratios were used in the second test; however the length of the phases was controlled using the online instruments. The denitrification phase was controlled by the NO_x-N analyser. The aeration, and as a result, the nitrification cycle started once the NO_x-N concentration dropped below 2 mg/L. Due to the time delay of 10 minutes in the bypass measurement loop and the measuring interval of the instrument, the actual NO_x-N-concentration in the reactor was usually already well below 1 mg/L. The nitrification cycle was controlled via the NH₄-N analyser. The setpoint for Ammonia was set to 5 mg/L, because the ammonium analyser had a longer sample interval and as a result a longer time delay (20 minutes). The nitrification (aeration) continued during the subsequent extraction phase which added additional time to the nitrification cycle. Typically, complete denitrification and nitrification could be achieved with these settings.

Table 2: Extract of results with analyser controlled cycle time (average values)

Exchange ratio [-]	VER = 0.1 _{contr}	VER = 0.2 _{contr}	VER = 0.3 _{contr}
Q _d [m ³ /d]	7.34	6.94	6.12
COD [mg/L]	315	261	227
SS [mg/L]	145	126	108
TKN [mg/L]	49.2	38.0	34.7
P _{tot} [mg/L]	6.1	5.4	4.7
MLSS [g/L]	15.6	13.7	11.1
BOD ₅ sludge loading rate [kg BOD ₅ /kg MLSS/d]	0.055	0.044	0.036
SRT [days]	28	31	41
t _{fill} [min]	8	18	30
t _{mix} [min]	7	35	67
t _{aerate} [min]*	12	8	20
t _{extract} [min]	13	34	62
N _{inorg,eff} [mg/L]	5.5	5.2	11.1

η_{DN} [%]	85.1	82.2	62.5
*	only considering aeration without permeate extraction		

By controlling the cycle times, the plant throughput was significantly increased (Table 2) with the exception of the exchange ratio of 0.3. At the same time the efficiency of the nitrogen removal was improved for all exchange rates. For the exchange ratio of 0.2_{contr} the theoretical elimination rate for the cycle setup ($\eta_{DN} = 1 - VER = 80\%$) was exceeded, which can be attributed to the simultaneous denitrification at the beginning of the aeration phase.

With the exchange rate of $VER = 0.1_{contr}$, it was difficult to control the cycle times due to the time delay of the online analyser in relation to the required response times. Because the average response time was about 40 minutes and the measured delay for NH_4-N was already 20 minutes, the “aeration without permeate extraction” cycle was often missed. The subsequent phase of extraction was not sufficient for a complete nitrification, which lead to an accumulation of ammonium in the system. This continued until the NH_4-N concentration of 5 mg/L was constantly exceeded and a long period of aeration was initiated. This effect led to elevated effluent concentrations.

3.3 Predicting the cycle time

One crucial design parameter for SBR plants is the cycle and reaction time. In case of sequencing batch membrane bioreactors, the current experienced based approach is not directly applicable, so that the usual estimation of the cycle times is imposed with increased uncertainties. Within the project the calculation of the cycle times was tested and will be presented and discussed specifically for the nitrification. For the denitrification, the approach is similar, but in that case the substrate consumption and the hydrolysis of particulate, easily degradable substrate into dissolved substrate must be considered as well.

The nitrification rate can be calculated using Equation 1 based on the ASM 1 (Gujer et al., 1987). This formula does not consider the incorporation of nitrogen into the biomass as this is described in a different process of the ASM 1. However, the incorporation of nitrogen can be considered as a percentage ratio e.g. 5% of BOD_5 or 2.5% of COD for the growth of biomass. The respective process rate is calculated using a reduced TKN starting concentration.

$$\frac{dS_{NO}}{dt} = \frac{1}{Y_A} \cdot \mu_A \cdot \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) \cdot \left(\frac{S_O}{K_{O,A} + S_O} \right) \cdot X_{BA} \quad \text{Eq. 1}$$

Based on the design TKN concentration and the design DO setpoints during the nitrification phase, it is possible to calculate the required time for the nitrification cycle once the autotrophic biomass concentration (X_{BA}) and the other relevant coefficients are available.

The concentration of the active autotrophic biomass (X_{BA}) can be calculated according to the German HSG Approach (Böhnke, 1989) using a steady state approach as follows:

$$X_{BA} = \frac{Y_A \cdot t_{SS,dim} \cdot q_R \cdot [S_{NH_4,N,av} - S_{NH_4,eff,av}]}{1 + b_A \cdot f_{T,BA} \cdot t_{SS,aerob}} \left[\frac{\text{kg MLSS}}{\text{m}^3} \right] \quad \text{Eq. 2}$$

with: X_{BA} = Concentration of autotrophic biomass in kg MLSS/m³
 Y_A = 0.15 kg MLSS/kg nitrogen eliminated (autotrophic biomass yield)

SRT_{tot} =	Total sludge retention time
q_R =	Volumetric loading rate
$S_{NH_4,N,av}$ =	Average concentration of ammonium nitrogen to be nitrified
$S_{NH_4,eff,av}$ =	Average concentration of ammonium nitrogen in the effluent
b_A =	0.05 day^{-1} (decay rate autotrophic bacteria)
$f_{T,bA}$ =	$1.09^{(T-15)}$ (temperature coefficient autotrophic bacteria decay)
SRT_{aerob} =	Aerobic sludge retention time

Similarly, the ratio of the heterotrophic biomass and the inert ratio of the activated sludge can be determined with the formulas of the HSG Approach (Böhnke, 1989). Table 3 shows a comparison of the active autotrophic and heterotrophic biomass ratios and the inert ratio for the different test periods as described before which were calculated with this approach.

Table 3: Calculated fractionation of the activated sludge

Volumetric exchange ratio (VER)	0.1	0.2	0.3	0.1 _{contr}	0.2 _{contr}	0.3 _{contr}
X_{BA} [kg MLSS/m ³]	0.17 (1.0 %)	0.13 (0.8 %)	0.22 (2.0 %)	0.24 (1.6 %)	0.19 (1.5 %)	0.16 (1.5 %)
X_H [kg MLSS/m ³]	2.66 (16.3 %)	2.75 (16.7 %)	3.57 (32.0 %)	3.88 (25.3 %)	3.51 (27.6 %)	2.65 (24.7 %)
X_I [kg MLSS/m ³]	13.50 (82.7 %)	13.63 (82.6 %)	7.37 (66.1 %)	11.21 (73.1 %)	9.04 (71.0 %)	7.94 (73.9 %)
X_{total} [kg MLSS/m ³]	16.33	16.51	11.15	15.33	12.74	10.75

For the other parameters required in Equation 1, such as half-saturation coefficients etc., a large amount of information based on practical experience is available. Within this project, two common sets of parameters were compared: the standard parameter set of the software package SIMBA (ifak, 1998) and a parameter set determined especially for SBR plants by Oles (1991). Those parameter sets were tested in a simulation study modelling the whole process with the ASM 1. The relevant parameters that are required to describe the nitrification according Eq. 1 are summarised and compared in Table 4.

Table 4: Tested kinetic and stoichiometric Parameters

Parameter	Unit	Value at 20°C	
		Oles (1991)	Ifak (1998)
Y_A	g COD (g N) ⁻¹	0.28	0.24
μ_A	day ⁻¹	0.75	0.8
K_{NH}	g NH ₃ -N m ⁻³	2.0	1.0
$K_{O,A}$	g O ₂ m ⁻³	0.4	0.4

Table 5 shows a comparison of the standard deviations for the different parameter sets based on the modelling study for the whole system using the ASM 1.

Table 5: Average standard deviations for NO_x-N and NH₄-N of the different parameter sets

Parameter set	σ NH ₄ -N [mg/l]	σ NO _x -N [mg/l]	$(\sigma \text{ NH}_4\text{-N} + \sigma \text{ NO}_x\text{-N})/2$ [mg/l]
ifak (1998)	1.20	0.93	1.07

The best results were achieved with the standard parameter set (ifak, 1998) due to the fact that Oles (1991) used values that were specific to particular wastewaters and plants. The values used in the standard parameter set have been compiled from the experiences of numerous software users and thus have a greater claim of general validity.

To finally determine the nitrification times using Equation 1, the temperature and the oxygen contents in the reactor during the nitrification phase have to be assumed in addition to the previously discussed parameters. Due to the very low oxygen concentration at the beginning of the aeration phase, the oxygen content has a strong influence on the determination of the theoretical nitrification times. Figure 2 directly compares the measured and the calculated times using the described approach. The bisecting line has been entered into the diagram as ideal value.

The fractionation of the influent for both the dynamic simulation and for the recalculation of the single cycles was done according to the recommendations of Leaflet No. 15 “Simulation of municipal wastewater treatment plants” of the North Rhine-Westphalia Environment Agency (LUA NRW, 1998). Information about the fractionation of the necessary influent parameters for the ASM 1 from few continuously measured parameters can be found in Rolfs et al. (2001).

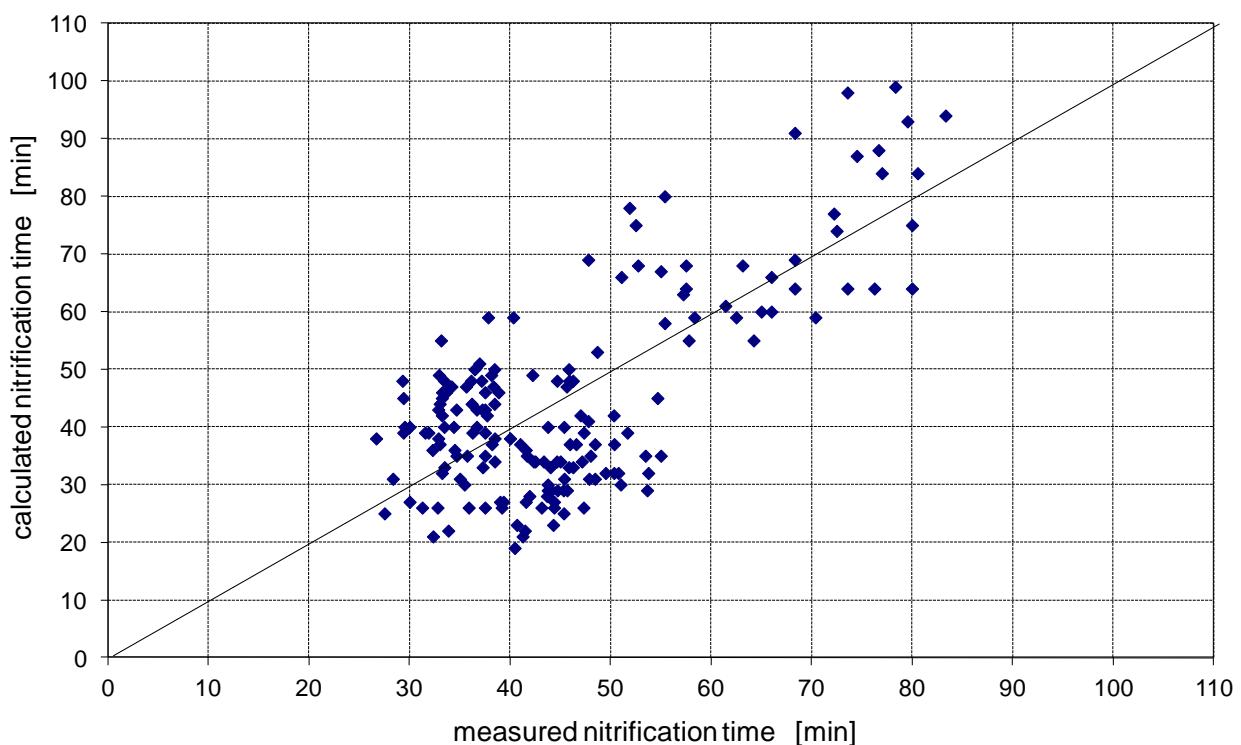


Figure 2: Comparison of calculated and measured nitrification times (determined from the daily average values)

The deviations noted in Figure 2 are a result of calculating nitrification times and the relevant parameters using daily average values. For the verification of the results, single cycles of different days and times were selected and the course of the nitrification was recalculated on the basis of the start values, the oxygen concentration, and the steady state determined ratio of the autotrophic biomass. Three exemplary cycles are presented in Figure 3.

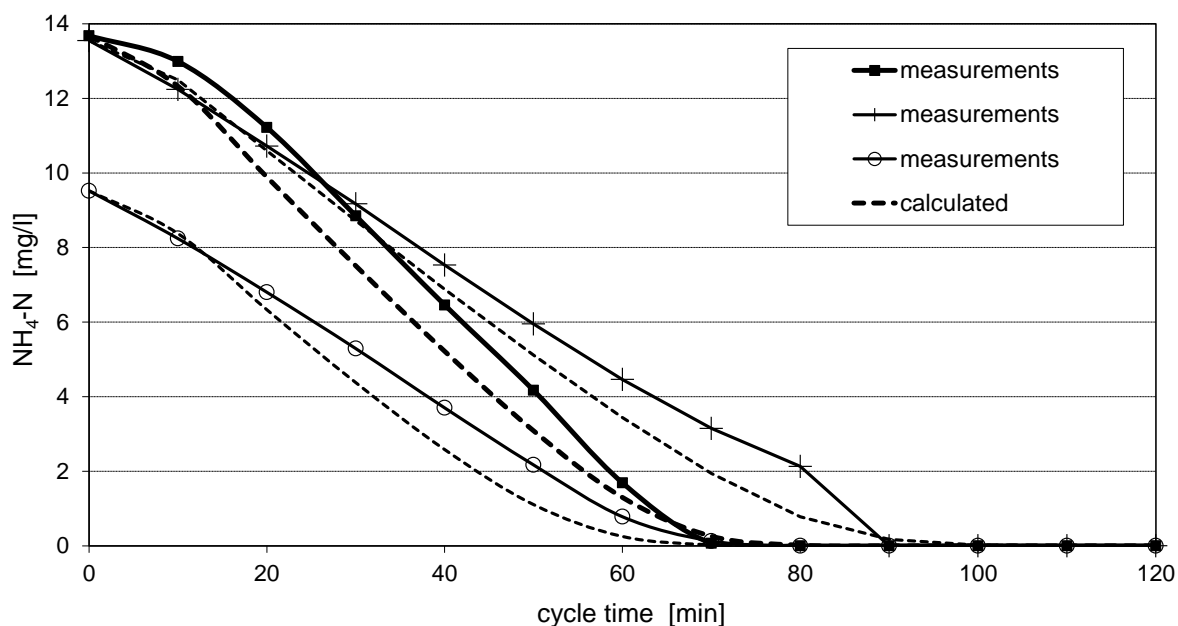


Figure 3: Comparison of single measured nitrification cycles with the respective calculated developments

The maximum deviation between the measured and the calculated cycle times was 10 minutes. Thus, it is possible to reliably determine the necessary nitrification time with the presented method. Similar results were also achieved for the denitrification times (Krampe, 2001). There, the deviation was slightly higher, as it is necessary to additionally consider other variables of the substrate consumption and of substrate storage processes which are not contained in the model.

In principle, the method presented here is also suitable for the predictive control of SBMBRs and conventional SBR plants. Some work has been conducted for conventional SBR plants in regard to real time control (Andreottola et al., 2003, Puig et al., 2005, Wiese et al., 2006 and Rönner-Holm and Holm, 2009). Yet, the method presented here is a simple initial approach towards the predictive calculation of the necessary cycle times for SBR systems. Especially in-situ online instruments using UV-Vis spectrometry and ion selective techniques offer the opportunity to provide fast and reliable data that can be used to improve the capacity and performance of existing SBR plants. To move towards the increased implementation in practice, further work on easy controllers is required.

4 SUMMARY AND CONCLUSIONS

Sequencing Batch Membrane Bioreactors have gained a lot of attraction over the last decade and significant research has been carried out. SBMBRs have been applied to a wide range of applications ranging from greywater to difficult industrial wastewaters. It is expected that in future, more SBMBR will be installed especially for smaller and decentralised applications.

During the design and layout it is important to predict the cycle times for the design conditions. For conventional SBR systems this prediction is usually based on experience from other plants. These experiences are currently not available for SBMBR systems as the typically increased MLSS concentrations result in significantly reduced cycle times compared to conventional SBRs. An overestimation of the cycle time will ultimately lead to an overdesign of the plants whereas an underprediction will result in capacity shortfalls or effluent quality deterioration. Therefore it is crucial to reliably predict the cycle time. Based on the operational data of the pilot plant and a simulation study of the ©IWA Publishing 2013. The definitive peer-reviewed and edited version of this article is published in *Water Science & Technology*, Volume 67, Issue 9, 2083-2090, 2013, doi:[10.2166/wst.2013.096](https://doi.org/10.2166/wst.2013.096) and is available at www.iwapublishing.com. This is the accepted version.

plant, this paper presents a way to calculate the cycle time for the nitrification, based on a steady state approach for the biomass calculation and the nitrification rate calculated using the relevant formula from the ASM1. Two different standard sets for relevant kinetic and stoichiometric parameters were tested and the ifak (1998) set was selected due to the lower standard deviation achieved during the modelling. No further calibration of the model was carried out to keep the approach as generic as possible. Using this method it was possible to calculate individual nitrification cycles with an accuracy of 10 minutes. The accuracy was reduced when applying the method to daily average cycles but this was expected. Nevertheless it was still possible to calculate the nitrification times with an accuracy of ± 20 minutes for most of the cases. A similar approach can be taken for the prediction of the denitrification cycles. This will provide more certainty for future design of SBMBR systems.

Secondly the advantage of improved cycle time control for SBMBR systems using online $\text{NH}_4\text{-N}$ and $\text{NO}_x\text{-N}$ analysers has been demonstrated for the treatment of municipal wastewater. Compared to a time based cycle time operation, the control of the cycle time using online data significantly increased the plant capacity while at the same time improved effluent quality. The next step is a predictive control of the cycle times based UV-Vis and ion selective online analysers in the sewage. Based on the described method of calculating the cycle times it is possible to develop predictive control systems for SBMBR systems but also for conventional SBR systems. This will ultimately lead to a very flexible treatment process that can utilise all the advantages that the SBMBR and SBR technology offer.

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REFERENCES

- Andreottola, G., Foladori, P., Ragazzi, M. (2001) On-line control of a SBR system for nitrogen removal from industrial wastewater, *Wat. Sci. Tech.*, 43(3), pp 93 – 100
- Bae, T.H., Han, S.H., Tak, T.M. (2003) Membrane sequencing batch reactor system for the treatment of dairy industry wastewater, *Process Biochemistry* 39, pp 221–231
- Böhnke, B. (1989) Bemessung der Stickstoffelimination in der Abwasserreinigung (HSG-Ansatz) (Dimensioning of the nitrogen removal in wastewater treatment), *Korrespondenz Abwasser*, No. 9, pp 1046 – 1061
- Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R., Matsuo, T. (1987). Activated Sludge Model No. 1, Scientific and technical report No. 1, IAWPRC, London
- Huggins, R., Drewes, J., Cath, T., Johnson, L. (2009) Evaluation of a Full Scale Hybrid Sequencing Batch/Membrane Bioreactor for Onsite Treatment of Domestic Wastewater, WEFTEC09. Orlando, FL, WaterEnvironment Federation, pp 6918 - 6924
- ifak (1998) Benutzerhandbuch für das Programm SIMBA 3.4+ (User manual SIMBA 3.4+), Institut für Automation und Kommunikation e.V., Magdeburg-Barleben
- Kang, I.J., Lee, C.H., Kim, K.J. (2003) Characteristics of microfiltration membranes in a membrane coupled sequencing batch reactor system, *Water Research* 37, pp 1192–1197
- Krampe, J. and Krauth, Kh. (2001) Sequencing batch reactor with submerged hollow fibre membranes for the biomass separation, *Wat. Sci. Tech.*, 43(3), pp 195 – 199

- Krampe, J. (2001) Das SBR-Membranbelebungsverfahren (Sequencing Batch Membrane Bioreactors), Stuttgarter Berichte zur Siedlungswasserwirtschaft, Band 163, Oldenbourg Verlag, München
- Kraume, M., Scheumann, R., Baban, A., El Amouri, B. (2010) Performance of a compact submerged membrane sequencing batch reactor (SM-SBR) for greywater treatment, *Desalination* 250, pp 1011 - 1013, doi:10.1016/j.desal.2009.09.093
- Laera, G., Jin, B., Lopez, A. (2011) Application of sequencing batch membrane bioreactors (SB-MBR) for the treatment of municipal wastewater, *Wat. Sci. Tech.*, 64(2), pp 391 - 396, doi:10.2166/wst.2011.622
- LUA NRW (1998) Simulation kommunaler Kläranlagen (Simulation of municipal wastewater treatment plants), Merkblatt Nr. 15 des Landesumweltamtes Nordrhein-Westfalen, Düsseldorf
- Martinez, J.M., Goltara, A., Mendez, R. (2003) Tannery wastewater treatment: comparison between SBR and MSBR, *Wat. Sci. Tech.: Water Supply* 3 (5–6), pp 275 - 282
- McAdam, E., Judd, S.J., Gildemeister, R., Drews, A., Kraume, M. (2005) Critical analysis of submerged membrane sequencing batch operating conditions, *Water Research*, 39, pp 4011 - 4019, doi:10.1016/j.watres.2005.07.028
- Meng, F., Yang, F. (2007) Fouling mechanisms of deflocculated sludge, normal sludge and bulking sludge in membrane bioreactors, *Journal of Membrane Science*, 305, pp 48 - 56, doi:10.1016/j.memsci.2007.07.038
- Oles, J. (1991) Verfahren zur Dimensionierung von SBR-Anlagen zur Nitrifikation und Denitrifikation (Method for the dimensioning of SBRs for nitrification and denitrification), *Hamburger Berichte zur Siedlungswasserwirtschaft*, Heft 8
- Puig, S., Corominas, L., Vives, M.T., Balaguer, M.D., Colprim, J. (2005) Development and Implementation of a Real-Time Control System for Nitrogen Removal Using OUR and ORP as End Points, *Ind. Eng. Chem. Res.*, 44 (9), pp 3367 – 3373, doi:10.1021/ie0488851
- Pressl, A., Zibuschka, F., Lindner, G. (2010) Der Anlagenbetrieb von Membranbioreaktoren bei kleinen Anschlussgrößen „Operation aspects of small membrane bioreactors“. *Österreichische Wasser- und Abfallwirtschaft*, 62 (11-12), pp 203 – 210, doi:10.1007/s00506-010-0239-5
- Rönner-Holm, S.G.E., Holm, N.C. (2009) Special automation and regulation strategies for enhancing sequencing batch reactor (SBR) performance, *Wat. Sci. Tech.*, 60(5), pp 1161 – 1172, doi:10.2166/wst.2009.466
- Rolfs, T., Bornemann, C., Kolisch, G., Londong, J. (2001) Provision of data for on-line simulation, *Wat. Sci. Tech.*, 43(11), pp 215 - 222
- Scheumann, R., Kraume, M. (2008) Influence of hydraulic retention time on the operation of a submerged membrane sequencing batch reactor (SM-SBR) for the treatment of greywater, *Desalination* 246, pp 444 - 451, doi:10.1016/j.desl.2008.03.066
- Serrano, D., Suarez, S., Lema, J.M., Omil, F. (2011) Removal of persistent pharmaceutical micropollutants from sewage by addition of PAC in a sequential membrane bioreactor, *Water Research*, 45, pp 5323 - 5333, doi:10.1016/j.watres.2011.07.037
- Shariati, S.R.P., Bonakdarpour, B., Zare, N., Ashtiani, F.Z. (2001) The effect of hydraulic retention time on the performance and fouling characteristics of membrane sequencing batch reactors used for the treatment of synthetic petroleum refinery wastewater, *Bioresource Technology*, 102, pp 7692 - 7699, doi:10.1016/j.biortech.2011.05.065
- Tu, X., Zhang, S., Xu, L., Zhang, M., Zhu, J. (2010) Performance and fouling characteristics in a membrane sequence batch reactor (MSBR) system coupled with aerobic granular sludge, *Desalination* 261, pp 191 - 196, doi:10.1016/j.desal.2010.03.034
- Vargas, A., Moreno-Andrade, I., Buirón, G. (2008) Controlled backwashing in a membrane sequencing batch reactor used for toxic wastewater treatment, *Journal of Membrane Science*, 320, pp 185 - 190, doi:10.1016/j.memsci.2008.03.073

- Wiese, J., Simon, J., Steinmetz, H. (2006) A process-dependent real-time controller for sequencing batch reactor plants: results of full-scale operation, *Wat. Sci. Tech.*, 53(4), pp 143 – 150, doi:10.2166/wst.2006.118
- Xi, X., Cui, Y., Wang, Z., Qian, J., Wang, J., Yang, L., Zhau, S. (2011) Study of dead-end microfiltration features in sequencing batch reactor (SBR) by optimized neural networks, *Desalination* 272, pp 27 - 35, doi:10.1016/j.desal.2010.12.049