Preprints of the 12th IFAC Symposium on Computer Applications in Biotechnology
The International Federation of Automatic Control
16-18, 2013, December. Mumbai, India

Simulating ultrasonic activated sludge disintegration for excess sludge reduction in SBR systems

H.H. Pham [*] **N. Lambert** [**] **P. Buffel** [**] **K. Van Eyck** [**]
R. Van den Broeck [*] **R. Dewil** [**] **I. Smets** [*]

[*] *Chemical Engineering Department, KU Leuven, W. de Croylaan 46, B-3001 Leuven, Belgium*
e-mail: [huyhoang.pham; nico.lambert; kwinten.vaneyck; rob.vandenbroeck; raf.dewil; ilse.smets]@cit.kuleuven.be
[**] *Laboratory for Environmental and Process Technology, Thomas More Campus De Nayer, 2860 Sint-Katelijne-Waver, Belgium*

Abstract: This paper presents an integrated mathematical model that is capable of predicting and assessing the impact of ultrasonic (US) treatment on the excess activated sludge production in a sequencing batch reactor (SBR) system. Such a model can be exploited to maximize the excess sludge reduction while minimizing the US operational costs in biological wastewater treatment systems. Biological processes in the reactor are simulated in Matlab®/Simulink by the ASM1 model into which two algebraic equations, which capture the US treatment, are integrated. Validation data series come from a pilot plant installed at two locations, i.e., at a communal wastewater treatment plant and at an industrial production site of a food flavor producing factory in Haasrode both in the Flanders region in Belgium. The results show that the excess sludge reduction from the SBR can be correctly predicted. A reduction of nearly 42% for the communal case study can be reported, while preliminary results for the industrial case study, characterized by a very high organic loading, are even more promising.

Keywords: wastewater treatment modeling, ultrasonic disintegration, excess activated sludge reduction.

1. INTRODUCTION

Notwithstanding the major advantages of biological wastewater treatment systems, the inherent production of excess sludge remains a significant financial burden. A number of methods, including mechanical or chemical treatment, have been used to reduce the excess amount of activated sludge. Among mechanical treatments, ultrasound is highly promising (Folador et al., 2010).

The main purpose of ultrasonic treatment of sludge is to promote cell lysis due to which organic compounds are released. Over the last few years, much research has been carried out to prove the advantages of ultrasound for activated sludge disintegration. Most reported applications of ultrasonic cell disintegrating are, however, situated in the field of pretreatment for anaerobic digestion by applying ultrasound on *waste* activated sludge. By disrupting the cell (floc) structures, this cellular organic matter is transformed in more easily accessible and more easily biodegradable matter for the anaerobic digestion. One of the most recent ones is a study on high-frequency ultrasound, in which floc disintegration and surfactants removal were combined (Gallipoli and Braguglia, 2012). In this research, the authors proved that sludge ultrasound treatment leads to an overall improvement of digestion performances. In the here presented research we specifically aim at excess sludge reduction by applying ultrasound on *return* activated sludge. The released organic matter due to the ultrasound disintegration is consumed in a process called *cryptic growth*. Due to the fact that the yield coefficient of biomass on substrate is less than one (most often around 0.6) the overall biomass production is reduced.

Only few studies focus on developing mathematical models for ultrasonic treatment (e.g., Li et al., 2010; Sahinkaya and Sevimli, 2012) and if they do, they do not consider the ultrasonic treatment in combination with the conventional activated sludge processes since their main interest is optimizing and improving the efficiency of the ultrasonic activated sludge treatment prior to sludge anaerobic digestion.

Being able to simulate how much organic matter will be released and how much excess sludge will be avoided in function of the ultrasound treatment settings, offers great advantages in optimizing the economics of the process. Furthermore, the released organic matter can be exploited as carbon source for, e.g., denitrification processes. To

[⋆] Work supported in part by Projects OT/10/035, OPTEC (Center-of-Excellence Optimization in Engineering) PFV/10/002 and SCORES4CHEM KP/09/005 of the KU Leuven, and by the IWT 090186 and IWT 110171 - TETRA-projects and the Belgian Program on Interuniversity Poles of Attraction, initiated by the Belgian Federal Science Policy Office.

Fig. 1. The SBR pilot plant of this study.

test the impact on the overall water purification efficiency, integration of an ultrasound model with a conventional activated sludge model is required.

Therefore, the aim of this paper is to develop an integrated mathematical model which captures the impact of ultrasound treatment on excess activated sludge production and which can later on be exploited in optimizing the operational settings of the US treatment. After the introduction of the materials and models (Section 2), the model implementation, calibration and validation is presented, the latter on the basis of two case studies (Section 3). Finally Section 4 summarizes the main conclusions of this work.

2. MATERIALS AND MODELS

2.1 Materials

This study relies on data from a pilot plant depicted in Figure 1, which has two parallel reactors of the SBR type (Bio1 and Bio2), each having a volume of 1 m^3. The pilot plant was installed at two different locations in Flanders, Belgium. From October, 2009 to December, 2011 the pilot plant was operated at the communal wastewater treatment plant of Aquafin in Mechelen-Nord, which will be denoted by WWTP Mechelen-Nord. From January 2012 until now, the reactor and all the equipments were moved to a food flavor producing factory in Haasrode, indicated as the WWTP Haasrode case study. While the former plant is characterized by a low organic loading and was tested as proof of principle, the latter exhibits an extremely high organic loading which induces, under normal operation, significant amounts of excess sludge for which, hence, the ultrasound treatment could be highly beneficial.

WWTP Mechelen-Nord

For the case in Mechelen-Nord, 0.9 m^3 is treated per day divided in 3 cycles, which each last, hence, for 8 hours. The settings are the following: the filling and aeration time is 5.5 hours followed by 0.5 hours final aeration. The settling phase lasts for 1 hour, during the last 10 minutes of which 20L of sludge is withdrawn and led to the ultrasonic equipment before being returned to the biodegradation tank during the first subsequent feeding phase. The decanting phase lasts for 1 hour.

While in general the aeration of the SBR system is steered by a more complicated scheme involving comparing the already evolved aeration time with the maximal aeration time and the nitrification time, the process at Mechelen-Nord can, due to the low COD input, easily reach 1 mg/L during the nitrification period. Thus, along the reaction phase (5.5 hours) the system alternately runs with 20 minutes of nitrification and 20 minutes of denitrification. When the dissolved oxygen (DO) reaches 3 mg/L during the aeration phase, the aeration is switched off and is turned on again when DO drops below 1 mg/L. When the aeration time has expired, the anoxic phase starts. During each 20 minutes of anoxic phase, influent is added to the reactor via a 200 L/h pump until the desired amount of wastewater is reached, i.e., 300 L/cycle. One of two reactors (Bio2) is connected to the ultrasonic treatment to examine its impact on sludge reduction and on the overall treatment performance. The sludge age is initially maintained at 25 days for both reactors by wasting 1/25 volume of the tanks every day (36 L/day and 12 L/cycle).

WWTP Haasrode

Due to the different compositions of the influent in Haasrode, i.e., a high organically loaded influent (expressed in Chemical Oxygen Demand - COD), operational settings of the SBR are adjusted accordingly. Only one cycle per day is implemented to treat 60 L/day. The settings are the following: the filling and aeration time is 16.5 + 3 hours, the first block is a sequence of aerated and anoxic (+ filling) phases while during the last 3 hours one continuously aerates. Then the reactor turns into a settling phase (1.5 hours) and decantation/rest phase (3 hours). During the aeration/anoxic+filling phase 1 hour long aeration phases are followed by 1 hour long filling and denitrification phases. The procedure is repeated until the feeding/aeration time (16.5 hours) is over. Dissolved oxygen during the aeration is controlled between 1 and 2 mg/L. The active volume of the reactor (while operating) is maintained at 500L. The SRT in the system is again kept at 25 days by wasting 1/25 of the reactor volume at the beginning of the continuous aeration phase, i.e., 20L. Thickened sludge for the US treatment is withdrawn from the reactors 50 mins after the settling phase starts. An effluent of 60L is discharged at the end of the settling phase.

Matlab®/Simulink implementation

Figure 2 shows how the two SBR systems (in Mechelen-Nord and Haasrode) are implemented in Simulink. The overall SBR model is built-up using the default blocks. These blocks are connected to each other by a single line, which will transform (one way) signals containing information of flow, concentration, time, etc. to the input ports of the receiving blocks. The three main blocks of an SBR cycle can be seen on the schematic diagram of the system in Figure 2, i.e., a reaction + filling, a settling and a decanting block. The biological processes are implemented in the reaction + filling block in which the alternating aerated and non-aerated phases are imposed. A point settler model is built-up and attributed to the block of settling. The decanting block regulates how the

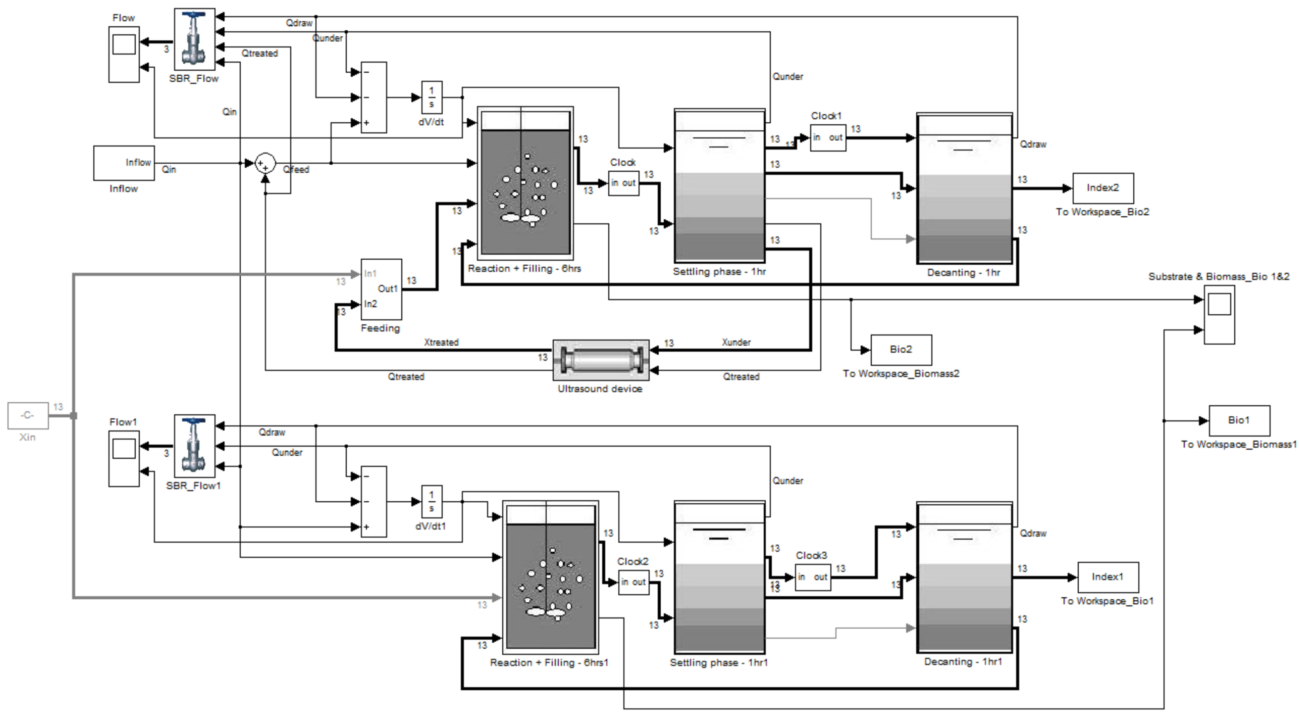

Fig. 2. Simuling implementation of SBR systems: Lower: control SBR Bio1 and upper: US treated SBR Bio2.

effluent is withdrawn from the reactor. Under each block, sub-systems are employed to be able to use common parameters for the internal calculations. In addition, in the Bio2 SBR an ultrasound block is integrated in which the algebraic equations for the US treatment are implemented. Apart from simple blocks which can be used directly from the library of Simulink, one also has to combine blocks to represent the typical working conditions of the SBR. For instance, due to the working principle of an SBR system, at the end of one cycle, the system has to be reset to start a new one. In this case an integrator has to be used with an external reset signal (when the time of a cycle has expired) and the conditions at the end of the previous cycle have to be used for the initial conditions of the current one.

Ultrasonic device

The plug-flow type ultrasonic device consists of a Bandelin reactor bloc SB 5.1-1002 with an array of 20 transducers and an ultrasound generator (1001 T). In this pilot system the activated sludge is recycled over the plug-flow reactor with a flow rate of 514 L/h. The system has a fixed frequency of 25 kHz, and a variable power output with a maximum of 1000W.

2.2 Models

Biodegradation

In order to simulate the biodegradation processes, the ASM1 model (Henze, 2000) has been employed. Input fractionation is done to transform the incoming measurements regarding organic material and nitrogen components, to state variables of the ASM1 model. The available averaged influent data is summarized in Table 1.

Settling

As said before, a point settler was selected to simulate the sedimentation process, such that we assume that all particulate components settle well with only a small fraction of them escaping through the effluent. A thickening factor and a non-settable fraction of suspended solids were used to calculate the concentration of the underflow and effluent biomass (MLSS) concentrations from the SBR. The thickening factor was derived from experimental data from the MLSS sensors in both reactors. The results showed that in most cases, the concentration of MLSS was doubled during the settling phase. Hence, a thickening factor of 2 is used and the non-settleable fraction is set to a default value of 0.005.

Ultrasonic sludge disintegration

The working principles of the ultrasonic device are based on the research on soluble COD (sCOD) release and instantaneous sludge reduction initiated by Lambert et al. (2010). A PLS based model was developed to predict instantaneous sludge reduction, as a result of low intensity ultrasonic sludge disintegration and cell lysis, depending on the initial mixed liquor suspended solid concentration, $MLSS_0$ ($gDS.L^{-1}$), the specific energy (Es, $KJ.kg\ DS^{-1}$)

Table 1. Averaged influent data at Mechelen-Nord and Haasrode.

Component (mg/L)	Mechelen-Nord	Haasrode
COD	224	14500
sCOD	183	7570
TN	39	498
TP	5	N/A
Ortho-P	4	N/A
NH_4-N	29	18
NO_3-N	1	28
SS	158	3217

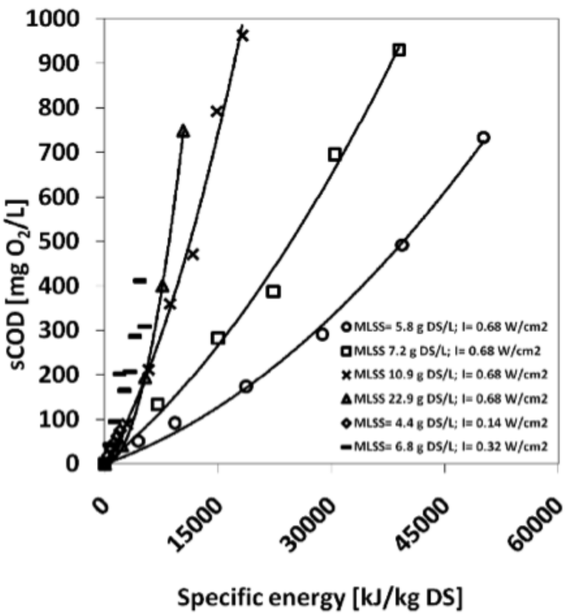

Fig. 3. sCOD change at different initial dry MLSS concentrations (4.4 − 22.9 g DS/L) and varying ultrasonic intensity values (0.14 − 0.68 W/cm^2).

and the acoustic intensity I, (W/cm^2). More specifically, a PLS model was developed to infer the relationship between the sCOD release, denoted with ΔsCOD and the $MLSS_0$ and acoustic intensity, on the basis of data like presented in Figure 3.

Given the non-linearity of the relationship, several non-linear transformations of the PLS input variables have been tested of which the best outcome is captured by Equation (1).

$$\begin{aligned}\ln(\Delta sCOD) &= -3.97897 + 0.83433 \cdot \ln E_S \\ &+ 0.75904 \cdot \ln(MLSS_0) - 0.39614 \cdot \ln(I) \quad (1)\end{aligned}$$

Afterwards, a relationship between the released amount of sCOD and the instantaneous sludge reduction is sought. Although there are already a lot of references in the literature about the release of sCOD as a result of sludge disintegration (e.g., Pilli et al., 2011), not much is known on the correlation between this sCOD release and the instantaneous sludge reduction as a result of ultrasonic sludge disintegration and cell lysis.

In general, following relationship is valid

$$MLVSS_t = MLVSS_0 - \frac{\Delta sCOD}{1000} \cdot \frac{1}{f_{cv}} \quad (2)$$

with f_{cv} the yield factor of sCOD on MLVSS.

Although it can be theoretically assumed that the release of 1.42 kg of sCOD in the supernatant liquid corresponds with a sludge reduction of 1 kg of MLSS (i.e., f_{cv} equal to 1.42), our experimental data show that the correlation between sCOD release and instantaneous MLVSS reduction is highly dependent on the specific energy. Figure 4 clearly depicts that low specific energies give rise to low sCOD/MLVSS ratios, which in turn causes a large instantaneous MLVSS reduction at low sCOD releases. Hence, the MLVSS reduction seems to be most profound at low specific energies. The best-fit for this data is captured by Equation (3).

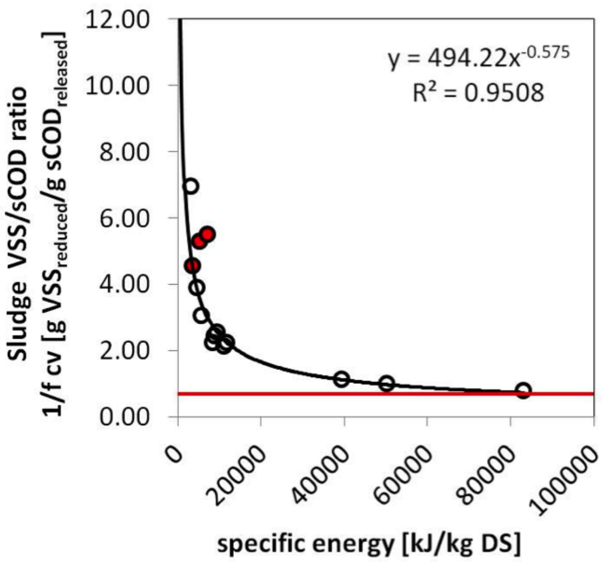

Fig. 4. Sludge sCOD/MLVSS ratio as a function of specific energy. Training and external validation sets are differentiated by open (○) and solid (●) circles, respectively.

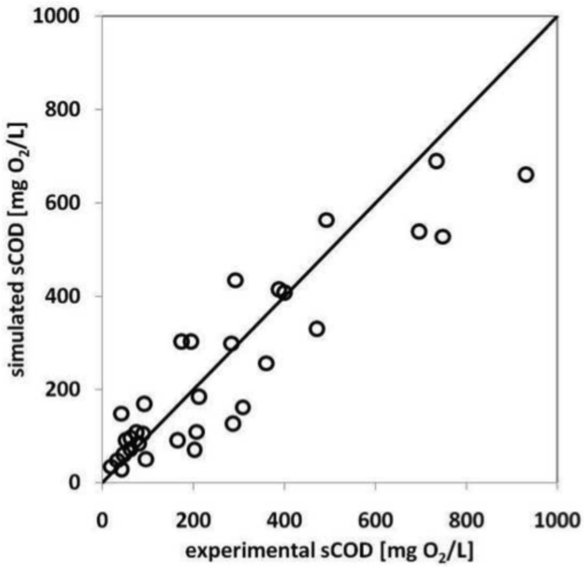

Fig. 5. Relation between simulated and experimental data for sCOD release in the supernatant liquid.

$$\frac{1}{f_{cv}} = 494.22 \cdot (Es)^{-0.575} \quad (3)$$

Validation of both submodels can be found in Figures 5 and 6.

As the concentration of biomass observed in ASM1 is active biomass (viable microbial biomass), and under the assumption that 50% of MLVSS is dead biomass,

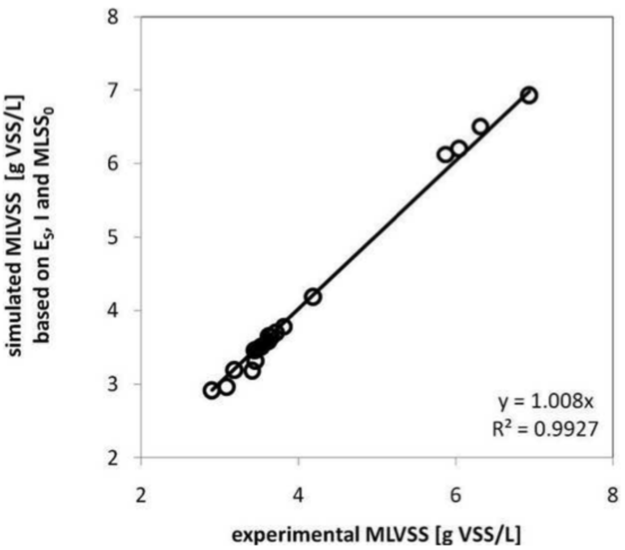

Fig. 6. Relation between simulated data and true data for MLVSS concentration. Training and external validation sets are differentiated by open (○) and solid (•) circles, respectively

the MLVSS will be equal to 2 times the sum of the heterotrophic (X_{BH}) and autotrophic (X_{BA}) biomass. Sampling and analysis results have shown that the ratio between MLVSS and MLSS was approximately 70% . This will be used to calculate the $MLSS_0$ in the above equations based on $MLVSS_0$. Furthermore, the sCOD values at the exit of the US device are assumed to be readily available organic matter, denoted by S_S in ASM1 terminology.

3. RESULTS

3.1 WWTP Mechelen-Nord

Mass balance

Firstly, the liquid mass balance was checked by verifying the incoming and outgoing flows of the SBR system. As an illustration the evolution of the flow and volume of Bio2 in Mechelen-Nord is depicted in Figures 7 and 8. During the last 10 mins of the 1 hour of settling phase, 12L is wasted from the reactor by an underflow of 1.728 m^3/d. In addition, the treated sludge flow from the sludge tank is taken into account, i.e., 20 L/cycle; due to which the under flow Q_{under} amounts to 4.608 m^3/d. In order to re-distribute the sludge flow to the normal inflow, 20L of treated sludge is added to the first subcycle. That means 20L is added during the first 20 minutes of denitrification with a magnitude of 1.44 m^3/d. Thus the influent to the SBR will be the sum of the normal influent (4.8 m^3/d) and the sludge flow (1.44 m^3/d), i.e., 6.24 m^3/d for the first subcycle. Treated water is withdrawn during 1 hour of decanting phase with a flow Q_{draw} of 6.912 m^3/d.

Calibration of the ASM1 model

As this study aims at validating the integrated model on real WWTP data, care has to be taken that a proper fit exists between the control SBR values and the real data. Since this study did not allow for a very in depth calibration of stoichiometric and kinetic parameters, the

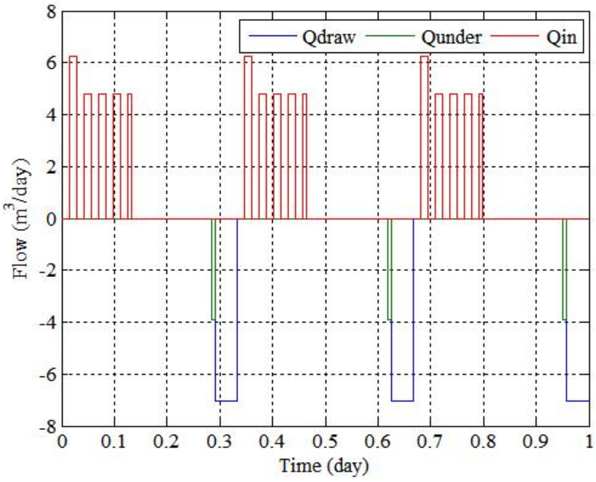

Fig. 7. Flow pattern during 1 cycle in SBR Bio2 at Mechelen-Nord.

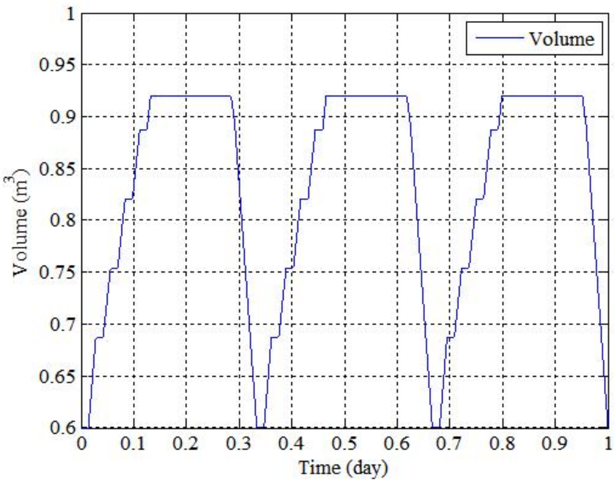

Fig. 8. Volume pattern during 1 cycle in SBR Bio2 at Mechelen-Nord.

default parameters were implemented in a preliminary testing phase. Herewith, we were, however, unable to attain the experimentally measured steady-state biomass concentrations during the biodegradation phases. Four parameters that have the largest influence on the biomass concentration in the ASM1 model were studied to select the most sensitive one, i.e., the maximum specific growth rate for heterotrophic biomass μ_H, the decay coefficient for heterotrophic biomass b_H, the correction factor for anoxic growth of heterotrophs η_g and the yield for heterotrophic growth Y_H. Simulation was first carried out with the default values of the above parameters, which can be seen from Table 2.

Table 2. Default values of ASM1 parameters.

ASM1 parameters	μ_H (day^{-1})	b_H (day^{-1})	η_g (-)	Y_H (gCOD/gCOD)
Default values	0.4	0.4	0.8	0.625

The influence of the four mentioned parameters was studied and while for the parameters μ_H, η_g and Y_H, the default values seemed reasonable, the decay coefficient value b_H was found to be high at 20^0C, i.e., 0.4. A line search optimization for this parameter has proved that a lower value is more suitable to express the evolution of biomass concentration in the reactor. Table 3 below shows the biomass concentration in the SBR at steady state with different values of b_H.

Table 3. Calibration of the decay rate parameter b_H

b_H (day^{-1})	0.4	0.3	0.2	0.1
Biomass (X_{BH}) (g/L)	0.59	0.72	0.91	1.14

It is evident that a higher biomass concentration is achieved when a low decay coefficient is employed. With a b_H value of 0.1, the active biomass concentration in the reactor is 1.14 g/L. Given that it is assumed to be 50% of the MLVSS, the latter will be 2.28 g/L, and the MLSS value is approximately 3.26 g/L. These values are found to be in line with the experimental data in the not treated Bio1 reactor. The selected value of the decay coefficient b_H was then also used for the US coupled Bio2 reactor.

With respect to the operational parameters of the ultrasound, the operational settings were 15000 KJ.kg DS^{-1} for the specific energy E_S and 0.2 W/cm^2 for the intensity I. It is obvious that in order for Bio2 to have (approximately) the same biomass concentration as in Bio1, less sludge can be wasted. With an SRT of 25 days, the simulated active biomass concentration is 0.79 g/L for Bio2 and 1.14 g/L for Bio1. To have an easy way of calculating the amount of excess sludge that can be avoided, it is simulated how much less one can waste per day if the target is to maintain the same biomass concentration as in the not treated reactor Bio1. Table 4 shows the observed biomass concentration in comparison with the values of wasted sludge and the corresponding sludge age SRT.

Table 4. Active biomass in the reactor with different SRT

Wasted sludge (L/cycle)	12	10	8	7	6
SRT (day)	25	30	37.5	43	50
Biomass (X_{BH}) (g/L)	0.79	0.9	1.05	1.14	1.24

It is clear from Table 4 that by wasting 7 L/cycle, the biomass concentration in Bio2 can be kept almost the same as in Bio1. A quick calculation shows that the amount of sludge that can be wasted less from Bio2 in comparison with Bio1 is 15 L/day, which represents a reduction of 42%. This also means that the sludge age in Bio2 will increase to 43 days instead of being 25 days as in Bio1.

3.2 WWTP Haasrode (on-going)

As described previously, due to the different compositions of the influent, 60L per day is treated in one cycle. With the experience gained from the case study of Mechelen-Nord, we expect to see the same or a better impact of the ultrasound disintegration when the system is applied in Haasrode. The same ASM1 kinetic and stoechiometric values have been employed as in the WWTP Mechelen-Nord case study.

The initial simulation results show that, in the control reactor Bio1, the active biomass concentration reaches in steady-state approximately 3 g/L while in the treated reactor Bio2 (with the same wastage of 20L and the same SRT of 25 days), the active biomass concentration is 2.5 g/L. Similarly to the other case study, we attempted to calculate the reduction in waste sludge when the waste sludge amount for the treated reactor is adjusted such that the steady-state concentration in the treated reactor is the same as in the control reactor. Unfortunately, due to the way the sludge is wasted, i.e., 20L of homogeneous solution when the reactor is mixed, the steady-state biomass concentration does not change a lot if the amount of waste sludge is increased. The results showed that, even with no wastage, the biomass in the Bio2 can only reach 2.8 g/L which is still lower than in Bio1, i.e., 3 g/L. Experimental validation is ongoing at the moment of writing. If the simulation results are confirmed, the advantages of using ultrasound for reducing the waste activated sludge are extremely significant for highly loaded wastewaters.

4. CONCLUSIONS

Based on the validation with real-life experimental data, the quality of the presented integrated model combining biological wastewater treatment with ultrasound sludge disintegration of a part of the return sludge, is illustrated. The results obtained for the case study of Mechelen-Nord have shown that about 42% less sludge can be wasted with represents a huge costs reduction. The experimental validation of the simulation for the highly loaded wastewater of an industrial plant is still ongoing.

REFERENCES

Folador, P., Andreottola, G., and Ziglo, G. (2010). *Sludge Reduction Technologies in Wastewater Treatment Plants*. IWA Publishing.

Gallipoli, A. and Braguglia, C. (2012). High-frequency ultrasound treatment of sludge: Combined effect of surfactants removal and floc disintegration. *Ultrasonics Sonochemistry*, 19, 864–871.

Henze, M. (2000). *Activated Sludge Models: ASM1, ASM2, ASM2d and ASM3.*

Lambert, N., Hulsmans, A., Houtmeyers, S., Van Impe, J., Smets, I., and Dewil, R. (2010). Cryptic growth by ultrasonic sludge disintegration of return activated sludge. In *6th European Meeting on Chemical Industry and Environment International*. Mechelen, Belgium.

Li, C., Liu, G., Jin, R., Zhou, J., and Wang, J. (2010). Kinetics model for combined (alkaline plus ultrasonic) sludge disintegration. *Bioresource Technology*, 101(22), 8555–8557.

Pilli, S., Bhunia, P., Yan, S., LeBlanc, R.J., Tyagi, R.D., and Surampalli, R.Y. (2011). Ultrasonic pretreatment of sludge: a review. *Ultrasonics Sonochemistry*, 18(1), 1–18.

Sahinkaya, S. and Sevimli, M.F. (2012). Effects and modelling of ultrasonic waste activated sludge disintegration. *Water and Environment Journal*, 1747–6585.