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A 1-D reactive Burger-Diehl settler model for SST denitrification considering clarifier geometry

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Abstract: A reactive settler model is pursued in order to better study the possible denitrification in secondary settling tanks (SSTs) and use it to reduce the pumping energy consumption for the internal nitrate recycle. The developed model is based on the industry standard 1-D Burger-Diehl (BD) settler model with explicit consideration of the clarifier geometry. The variation of surface area with depth needs to be implemented into the settler model for good prediction of the biomass concentration profile, total sludge mass and the reaction rates. If not, unrealistic changes in model parameters are required to fit the data, ultimately leading to errors in further scenario analysis and system operation.

Keywords: Reactive settling, post-denitrification, separation process modelling, secondary sedimentation

Introduction

SSTs are used for the gravity separation of microorganisms from the effluent in water resource recovery facilities (WRRFs). Through settling, a significant amount of the overall sludge inventory of the treatment plant can be stored in the bottom of the SST. At long residence times in the settler and with incomplete denitrification in the biological reactors, denitrification can take place at the bottom of the settling tank, where the concentration of sludge is high, nitrate levels are still substantial and oxygen is no longer present (Siegrist et. al., 1995). The combination of these biokinetic processes and physical settling phenomena occurring in the settler lead to so-called reactive settlers.

As this and other studies demonstrate reactive settling is a research topic that warrants further investigation to correctly analyse a WRRF's overall capacity for nitrogen removal including the contribution of SST denitrification. Exploiting SST denitrification may have a great potential for improved overall N removal and better effluent quality. Moreover, it only requires small operational changes, i.e. increasing the sludge blanket height (SBH) and keeping it at a desirable level. Furthermore, enhanced denitrification in the SST can -for the same N-removal- allow reducing internal recycle pumping in the biological reactors and thus result in significant saving in energy consumption and costs. In addition, external carbon that might be needed to reach a desired N removal, may be partially eliminated. However, strong denitrification during overloaded clarifier conditions could lead to N_2 gas induced rising sludge and be detrimental to the plant's efficiency (Henze et al., 1993). Detailed process understanding is thus needed to ensure safe and efficient system operation.

Previous modelling efforts have mostly considered SSTs as non-reactive, but some studies have reported the occurrence of biological reactions and reactive settler models have been developed (Koch et al., 1999; Gernaey et al., 2006; Burger et al, 2016). A prerequisite for reliable prediction of the biological reactions is an accurate calculation of the biomass concentration profile along the sludge blanket (SB). Relevant in this respect is that in the industry-standard Burger-Diehl (BD) model, the surface area is assumed the same at all depths. However, the bottom of a real SST is generally sloped and the surface area thus varies with depth – for an example see Figure 1 (De Clercq, 2003). Depending on the fraction of SST volume that is sloped, it may be important to actually model it. Indeed, this surface area variation affects the settling flux, thickening behaviour, biomass concentration and thus reaction rates at the bottom of the SST.

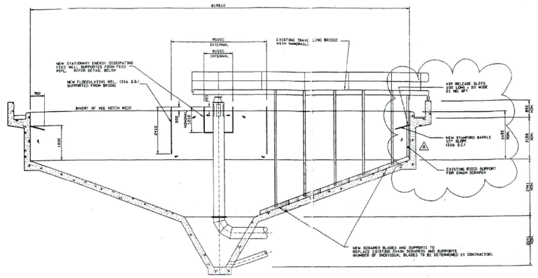

Figure 1 Cross-section of the Oxley Creek circular SST (De Clercq, 2003) (38% of the total volume is in the sloped part)

In order to take advantage of the possible denitrification process in the SSTs and use it for reducing the overall pumping energy consumption, it is fundamental to construct a reliable reactive settler model and research is required to link settling behaviour of activated sludge with operational conditions and denitrification efficiency. Mathematical models that are able to represent the sedimentation and compression processes in SSTs in combination with biological reactions have great potential from a practical perspective to improve overall N removal.

Within this study, a reactive settler model is developed based on the industry standard 1-D BD settling model with consideration of specific clarifier geometry.

Material and Methods

A detailed measurement campaign was carried out to quantify the N-removal potential of a SST (with a 32% conical volume) and to obtain data for development and calibration of the reactive settler model (Kirim et. al., 2019). Within this experimental work, different operational scenarios were applied to create different sludge blanket heights (SBH) and sludge denitrifying activity levels (Table 1 & Figure 2). The objective of the study was to better understand reactive settling and denitrification performance under three different operational scenarios. It was aimed to increase the SBH in Scenarios 2 and 3 through reducing the sludge recycle (RAS) and increasing the nitrate loading to the settler in Scenario 3 by reducing the internal recycle (IR) in the biological reactor.

Table 1 Experimental work operational scenarios

Scenario	Operational Change	High NO_3-N load (>18 mg/L)	SBH	Aim
1	-	-	Low	Reference conditions
2	Reduced RAS	-	High	Effect of high SBH
3	Reduced RAS & IR	+	High	Effect of high NO_3-N load

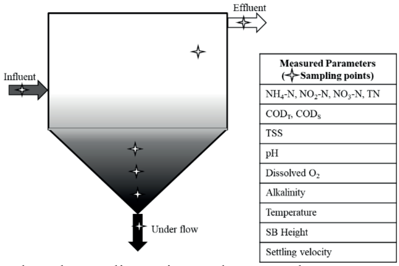

Figure 2 Experimental work sampling points and measured parameters

The state-of-the-art 1-D settling model –the BD model- which includes compression at high TSS concentrations was used as the settling model. The standard 1-D BD model only considers the vertical dimension along the SST and mass balance equations are formulated based on a constant surface area for each layer. For the hindered settling of the flocculated particles, the Takacs settling velocity function was used describing that the settling velocity decreases or becomes zero at low concentrations (Takacs et al., 1991). The ASM1 biokinetic model was chosen to model the reactions of carbon and N removal (Henze et al., 2000). The reactive SST model was implemented in WEST (mikebydhi.com). The input file was defined by a constant outflow of a bioreactor (Figure 3). Simulations were run till steady state.

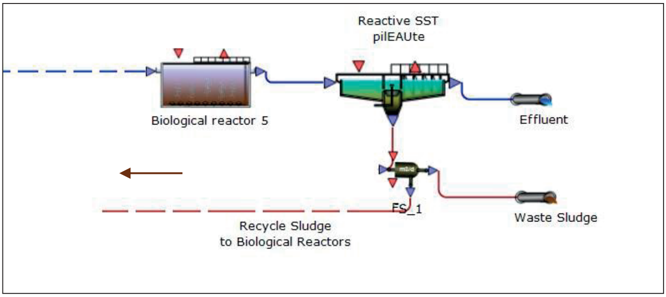

Figure 3 Reactive settler model layout

Results and Discussion

In the measurement campaign, it was observed that the SB consists of 2 zones in which denitrification occurs at different rates depending on the biomass concentration and the HRT. The upper part, from the feeding point to the top of the SB, acts as an endogenous post-denitrification zone in which NO_3-N removal occurs with relatively low efficiency because of the low biomass concentration. The lower part of the SB from the feeding point down to the bottom of the SST becomes a high rate reactor with concentrated biomass where significant denitrification occurs. The results show a consistent 90-95% nitrate removal in this zone, even for the high nitrate loading to the SST in Scenario 3.

The reactive settler model in which biological conversions and physical sedimentation occur simultaneously is developed in two steps. In the first step, The BD 1-D settling model is combined with the ASM1 biokinetic model included into each layer of the settling model. Similar as in standard settling models, the surface area is kept constant throughout the clarifier's depth. The PDE describing the settling behaviour over the depth of the settler (Bürger et al., 2013) is discretized in 16 layers and the mass balance for each of the 7 soluble and 6 particulate components is solved over each of these layers. Figure 4 shows the model results for TSS and NO_3-N along the 16 layers in the SST with default model parameters.

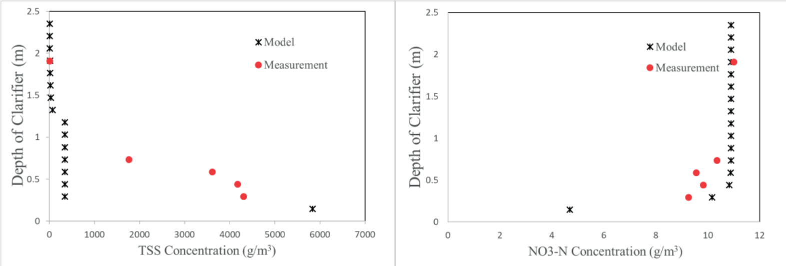

Figure 4 Constant area reactive Burger-Diehl model TSS (left) and NO_3-N (right) concentration profiles for reference scenario with default model parameters

The NO_3-N concentration decreases in the bottom layers of the SST (where the TSS concentration is substantial) due to the active denitrification process. However, it is not possible to obtain a representative SB profile with the default model parameters. Figure 5 shows the model results for the reference scenario after calibration for settling parameters v_0, r_H, $C_{critical\ for\ compression}$.

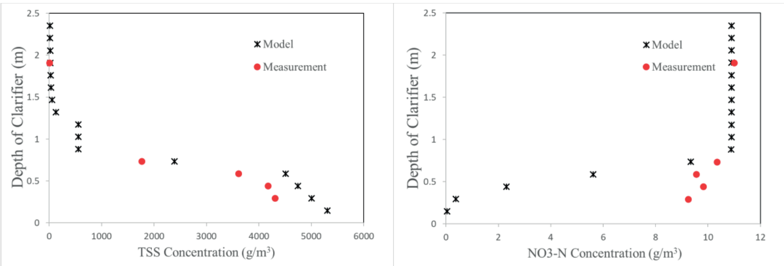

Figure 5 Constant area reactive Burger-Diehl model TSS (left) and NO_3-N (right) concentration profiles for reference scenario with calibrated settler model parameters (default biokinetic parameters)

Creating a representative SB concentration profile in terms of TSS with the current model is only possible when the hindered settling velocity of the flocculated particles is reduced and compression starts at low TSS concentrations. However, this gives way too low values for the NO_3-N concentration profile when using the default biokinetic model parameters. The measurements show that in reality, the denitrification is not as efficient in the reference scenario. Thus, the current model is overpredicting the denitrification rate and would require calibration of the biokinetic parameters. However, biokinetic parameter values should be obtained from the calibration of the biological reactor of the WRRF.

In addition to a proper SB concentration profile, the total sludge mass in the settling tank is another indicator of the quality of the reactive SST model. With the constant area model (results presented in Figure 5), the total sludge mass in the SB is almost 4 times that of the real mass of sludge calculated from the TSS measurement results for the reference scenario.

Figure 6 shows the preliminary model and measurement results for all the different scenarios, both for TSS and NO3-N. The model was calibrated for the settling velocity and compression parameters for each scenario. In Figure 6, the diameter of the circles is proportional to the measured concentrations that are shown in grey whereas model predictions are shown in black. The model results for each layer can be compared with the measurement result by looking at the agreement of the diameter of the circles. Comparable diameters of the model prediction and measurement results means a better model fit.

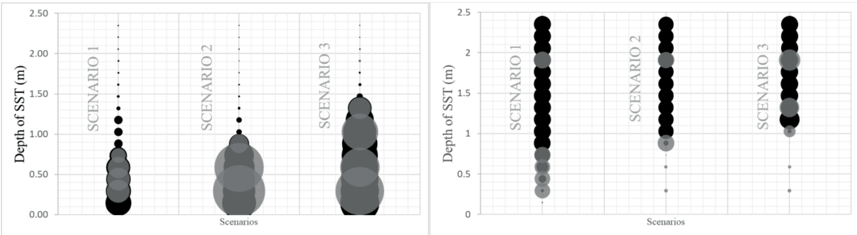

Figure 6 Model vs measurement results for TSS (left) and NO_3-N (right) with constant area SST with default biokinetic parameters and settling parameters calibrated for the 3 tested operational scenarios

With the current model, even though it is possible to improve the sludge blanket and sludge concentration predictions by calibrating the settling and compression parameters, it requires unrealistic parameter values and leads to a wrong calculation of the sludge mass and the efficiency of the biokinetic processes in the SST. It can thus be concluded that the current model has a structural error. Since the model does not include the varying surface area of the SST, the downward convective velocity (calculated as flow over surface area) is underpredicted causing TSS to accumulate in the bottom layers. In reality, the reduced surface area at the bottom of the SST causes the outflow velocity to increase and thus sludge to leave the settler faster. Hence, the assumption of constant surface area leads to an unrealistic sludge mass accumulation. Consequently, the efficiency of biokinetic reactions (such as the denitrification rate) is overpredicted.

For that reason, in the second step of model development, the clarifier geometry was implemented in the reactive settler model. The surface area and volume of the layers in the conic section of the bottom are now calculated by considering their conical frustum geometry (Figure 7). The flux calculation and mass balances were adjusted based on the varying surface area and volume of each layer.

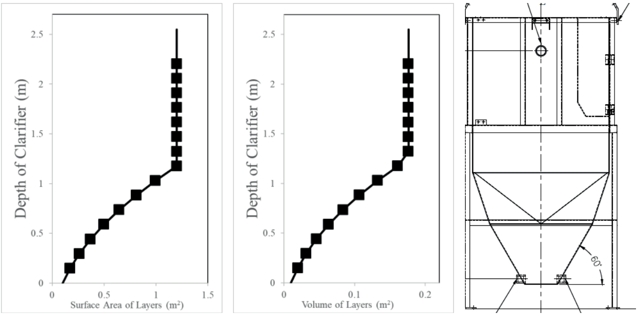

Figure 7 Varying surface area and volume of each layer calculated by the model and actual shape of the SST

Figure 8 shows results for TSS and NO_3-N with the new geometry model using default model parameters. Model predictions of TSS and thus NO_3-N were significantly improved through the SB when the actual clarifier geometry is used.

Figure 9 shows the calibrated model results for the BD reactive settler model with realistic clarifier geometry. The concentration profiles through the SB are close to the measured values and only small changes were needed in settling velocity parameters compared to typical values and no change had to be made to the default compression parameters.

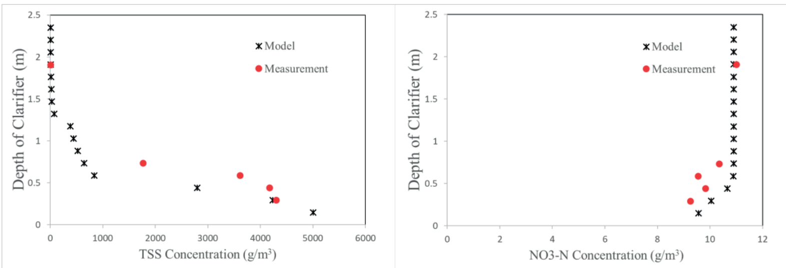

Figure 8 Reactive Burger-Diehl model with clarifier geometry TSS (left) and NO_3-N (right) concentration profiles for reference scenario with default model parameters

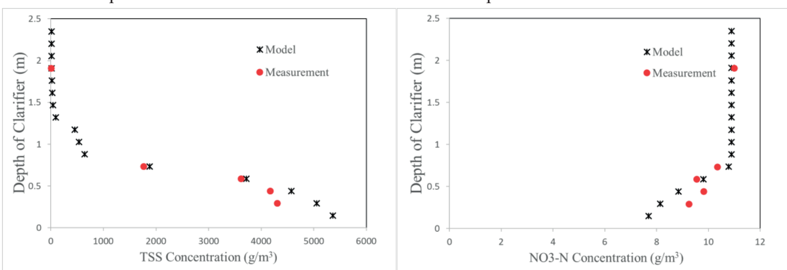

Figure 9 Reactive Burger-Diehl model with clarifier geometry TSS (left) and NO_3-N (right) concentration profiles for reference scenario with calibrated settler model parameters (default biokinetic parameters)

The revision of the model structure with varying surface area and volume of each layer eliminates the necessity to change model parameters unrealistically, both for settling and biokinetic processes. When it comes to the total sludge mass in the SB, the final version of the model gave a good approximation (15% underestimation) of the real sludge mass as calculated from the measured data for the reference scenario. The denitrification efficiency is much more realistic in the bottom layers (see also Figure 5). The final model and measurement results through the SB for the different scenarios are shown in Figure 10, both for TSS and NO_3-N. Note that the same optimal parameter set was used for all scenarios.

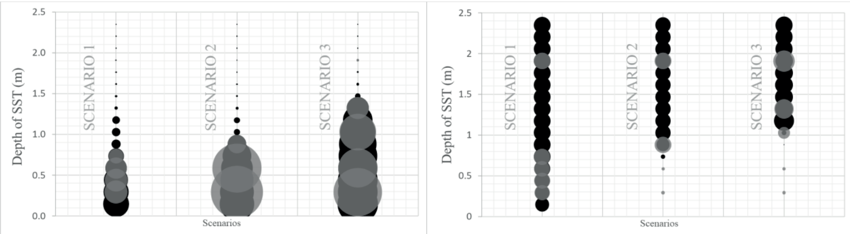

Figure 10 Model vs measurement results for TSS and NO_3-N (right) with varying diameter SST

The TSS concentration through the SB could be predicted well if the settling velocity is increased and compression takes place at higher TSS concentrations. The calibrated settling velocity and compression model parameters are in the default's range. However, similar to the previous version of the model, it is not possible to reach biomass concentrations as high as in reality in the deep layers of the SST. The increased sludge density leads to much higher TSS concentrations at the bottom of the SST and it is not possible to capture those concentrations with the current model structure, even if compression is ignored. It is known that the exponential hindered settling velocity function leads to underestimate the settling behaviour at high concentrations (Torfs et. al., 2017) and, possibly, another settling velocity function may give even better results.

In terms of the calibration of biokinetic reactions, the model results show that these parameters did not need to be calibrated to get close model fits for DO and NO_3-N. Since the activated sludge in a WRRF moves from the biological reactor to the SST, the biokinetic properties of the biomass should be the same in both the biological reactor and SST. For that reason, in a plant-wide model which comprises a reactive SST model, the values for the biokinetic parameters should be determined in the calibration of the biological reactor model and the same calibrated biokinetic model parameter values should be applied in the reactive settler model.

Conclusions

Within this study, a reliable reactive settler model was pursued in order to better study denitrification in SSTs and use it to reduce the energy consumption by internal recycle pumping. The unique experimental results obtained on an actual reactive settler allowed demonstrating the large potential for improved N-removal through reactive settlers. It was observed that it is possible to achieve denitrification in the SST at different rates depending on the biomass concentration and the HRT in the SST.

A 1-D reactive settler model including sedimentation and compression processes in combination with biological reactions was used to describe the reactive settler. Preliminary calibration showed that unrealistic changes in model parameters are required to fit the observations, which may lead to errors in further scenario analysis. This unrealistic calibration was attributed to a model structure error related to the assumption of constant area throughout the clarifier depth. Indeed, an unrealistic overall sludge mass in the SST is calculated if the conic shape is not considered. Hence, the actual clarifier geometry has to be considered when modelling a reactive settler.

Therefore, a new reactive settler model was developed that is able to take into account different clarifier geometries. The developed model is able to predict realistic SB concentration profiles without any change in the model parameters independent of whether biological reactions are considered. It is shown that the varying surface area cannot be excluded from the model since its variation affects the settling flux and compression of particles. The model results also show that the biokinetic parameters do not need to be calibrated to get close model fits for DO and NO_3-N. It is confirmed that the values of the biokinetic model parameters in the reactive settler model should be the same as the calibrated values for the biological reactor in a plant-wide model.

The developed model gives better predictions of profiles through the SB and thus warrants a closer look at the use of classic 1-D settling models in case of modelling of reactive settling as well as other settling studies where a varying cross-sectional area is present.

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