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Analysing sludge balance in activated sludge systems with a novel mass transport model

M. Patziger, H. Kainz, M. Hunze and J. Józsa

ABSTRACT

In activated sludge systems the mechanically treated wastewater is biologically cleaned by biomass (activated sludge). The basic requirement of an efficient biological wastewater treatment is to have as a high biomass concentration in the biological reactor (BR) as possible. The activated sludge balance in activated sludge systems is controlled by the settling, thickening, scraper mechanism in the secondary settling tank (SST) and sludge returning. These processes aim at keeping maximum sludge mass in the BR and minimum sludge mass in the SST even in peak flow events (storm water flow). It can be, however, only reached by a high SST performance. The main physical processes and boundary conditions such as inhomogeneous turbulent flow, geometrical features of the SST, wastewater treatment plant (WWTP) load, return sludge flow, sludge volume index etc. all influence settling thickening and sludge returning. In the paper a novel mass transport model of an activated sludge system is presented which involves a 2-dimensional SST model coupled with a mixed reactor model of the biological reactor. It makes possible to investigate different sludge returning strategies and their influence on the sludge balance of the investigated activated sludge system, furthermore, the processes determining the flow and concentration patterns in the SST. The paper gives an overview on the first promising model results of a prevailing peak flow event investigation at the WWTP of Graz.

Key words | activated sludge system, biological wastewater treatment, computational fluid dynamics, secondary settling tank, sludge recirculation

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INTRODUCTION

As is known in WWTP operation principles, sludge returning aims at keeping the activated sludge flux from the SST (secondary settling task) into the BR (biological reactor) as high as possible, without affecting the processes within the SST by too high SST load ($Q + Q_{RS}$), enhanced by the return sludge flow. As part of an optimized sludge returning strategy, when inner flow and mass transport processes of the SST due to dynamical load have to be considered, the recycled sludge mass rate can be maximised in a way achieving a low sludge mass within the SST and a high sludge mass within the BR (Ekama *et al.* 1997; Larsen 1977; Freimann 1999; Armbruster *et al.* 2001). In common practice three essential, different sludge returning strategies are used: (1) applying a constant return sludge flux independent from the current load of the WWTP (Q_{RS} = const.), (2) adaptation of the return sludge flow rate to the current load of the WWTP with a constant recycling ratio ($RV = Q_{RS}/Q$ = const.), and (3) increasing the return sludge flux in a way proportional to the increasing load of the WWTP, applied, however, above a threshold inflow and somewhat shifted in time. Thereby a lot of scientific and practical questions arise.

(1) In order to reach an optimal sludge returning strategy should the return sludge flow be left constant or increased with increasing WWTP load? (2) What is the optimal return sludge flow rate in case of applying constant return sludge flow independent from the current WWTP load to assure an overall

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efficiency both for dry weather (that is low load) and for storm water flow events (that is peak load)? (3) In case of an adapted sludge return contribution to the WWTP load what is the optimal constant return sludge ratio? (4) What inflow rate would be an optimum threshold value to begin to increase the return sludge flow rate proportional to the increasing WWTP load, furthermore, what would be the optimum of this ratio in the increasing and decreasing load periods? (5) Finally what is the influence of the sludge volume index on the choice of a sludge returning strategy?

The systematic investigation of these questions only by measurements at operating wastewater treatment plants is almost impossible. The main reason for that is the high scattering of the peak load patterns, which makes individual measurements difficult to compare to each other. To carry out a systematic comparison of sludge returning strategies each of them has to be investigated by applying the same peak flow event and the same sludge volume index. Numerical simulations of the system behaviour are therefore a helpful tool. In coupled models of activated sludge systems to date, only 0- and 1-dimensional SST models have been used. These models are, however, not able to consider important details with high relevance, such as the inner hydraulic behaviour of the SST and the effect of the different sludge return strategies on the flow and concentration patterns in the SST. In this paper the main result of an investigation is presented which was carried out by a new mass balance model of an activated sludge system in which an axisymmetric 2-dimensional SST model and a mixing reactor for considering the BR are coupled. This approach enables the investigation of the above mentioned questions and provides a detailed insight into the complex flow and transport processes in the SST during the investigated time period. The model calibration and verification was carried out for the WWTP of Graz.

MATERIALS AND METHODS

The numerical model

The scheme of the mass transport model is shown in Figure 1. It consists of a dynamic coupling the inhomogeneous turbulent flow within the SST including sludge transport, settling and thickening, with the BR via mass transfer

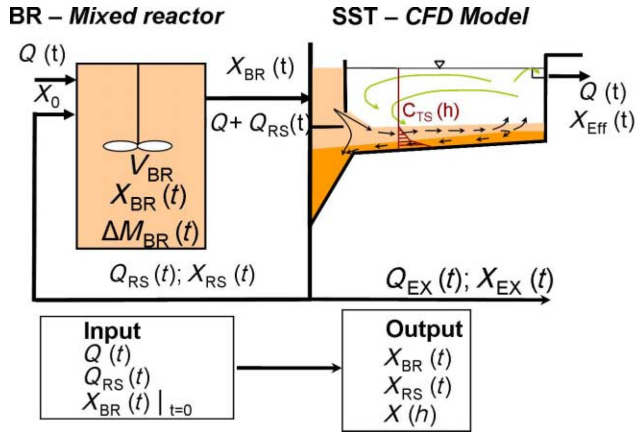

Figure 1 | Scheme of the mass transport model.

between BR and SST (Patziger *et al.* 2005) in unsteady load conditions.

It is presumed, that the suspended solids concentration (SS) of the inflow of the biological reactor (X_0) and sludge growth during the simulated time period have the same range of dimension as the excess sludge mass flux ($Q_{EX}{\cdot}X_{EX}$). Owing to this assumption the suspended solids concentration in the inflow rate of the biological reactor (X_0), the sludge growth during the simulated time period as well as the excess sludge mass flux ($Q_{EX}{\cdot}X_{EX}$) are neglected.

Circular secondary settling tanks can be reasonably investigated by an axisymmetric approach. The turbulent flow is modelled by the Reynolds-averaged Navier-Stokes equations with a k-ε turbulence closure (Rodi 1980). Transport processes are described by an advection-diffusion equation with terms describing settling and thickening, in which Hunze (2005) have implemented special modules for settling, density and rheology features, largely utilising the modified version of the settling function of Takács *et al.* (1991). The governing equations are numerically solved by the CFD code FLUENT 6 by means of an implicit unsteady segregated solver on a boundary-fitted finite volume grid (Patziger *et al.* 2005). In the BR a simple mixed reactor model solves the mass balance equation without considering source or sink terms.

Input parameters are the SST geometry, the volume of the BR (V_{BR}), the WWTP load time series ($Q(t)$), the time series of the return sludge flow rate ($Q_{RS}(t)$) and the initial value of the suspended solids concentration in the BR ($X_{BR}(t)|t_0$). The output parameters are: the flow and concentration pattern in the SST during the simulated time period, the time series of the return sludge concentration ($X_{RS}(t)$) and the time series of the suspended solids concentration in the BR ($X_{BR}(t)$), furthermore, the concentration of the outflow, the return sludge and the sludge transfer from the biological reactor in the SST.

At the beginning of the simulation in the SST clear water is defined as initial condition. As the first step of the simulation the SST is to generate reasonable initial conditions for the simulation of the sludge related processes. In doing that we fill up the SST with suspended solids by setting constant SST load Q and X_{BR} at the inlet (mostly the measured values valid in the beginning of the simulation), as well as outflow rate and return sludge flow rate Q and Q_{RS} at the outlet boundaries, then running the model until internal steady-state is reached. The simulation of a time period of 6 h usually results in equilibrium conditions of the SST. Once the equilibrium conditions of the SST are reached, the fluxes $(Q + Q_{RS})\cdot X_{BR}$ entering the SST are equal to the fluxes $(Q_{RS}\cdot X_{RS} + Q^{*}X_{Eff})$ leaving it. At that time the mixed reactor is also activated and the dynamic simulation of the WWTP operation by applying the measured load time series combined with the return sludge flow rate time series begins.

Model validation

The investigations focused on one of the four circular SSTs of the WWTP of Graz, seen in Figure 2, in which extensive measurements were performed in order to collect good quality validation data (Patziger *et al.* 2005).

During the flow and concentration measurements the hydraulic load, inflow and the return sludge concentration as well as the effluent quality in the tanks were continuously sampled. The first investigations including flow and SS concentration measurements were carried out in a period with nearly steady-state hydraulic load. The inflow concentrations ranged between 4.2 and 4.5 g/l in the measuring period.

Three-dimensional velocity measurements were carried out by a Nortek-Vector ADV; 90 s long velocity vector time series with 16 Hz sampling rate were obtained in the raster nodes; SS concentrations were measured in the same raster by an Endress & Hauser optical turbidity meter, calibrated for the SS features of the tank. Concentration profiles were obtained at every 2 cm in the measuring verticals by winching the sensor at constant speed. From numerical modelling point of view the two most important sludge characteristics are the sludge volume index SVI and the settling velocity v_s of the sludge. In the investigated plant the SVI is usually around 70 l/kg. As is known, the settling velocity is the function of the local concentration (Krebs 1991), which was investigated in a 2,000 mm high 300 mm diameter settling column, large enough to avoid undesirable wall effects. The analysis resulted in a settling function of SS slightly modified compared to that given by Takács *et al.* (1991).

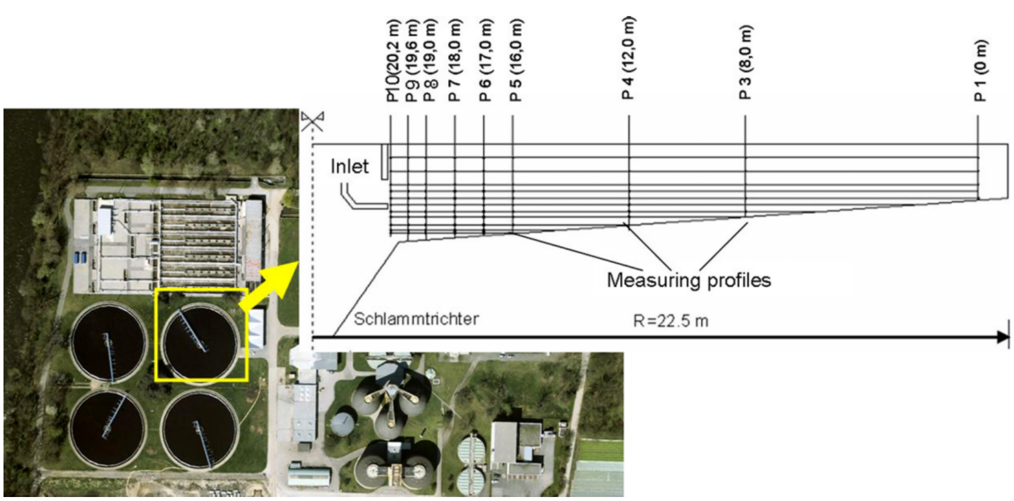

Figure 2 | Top view of the secondary settling tanks in the WWTP of Graz with displaying the geometry and measuring raster of the investigated tank.

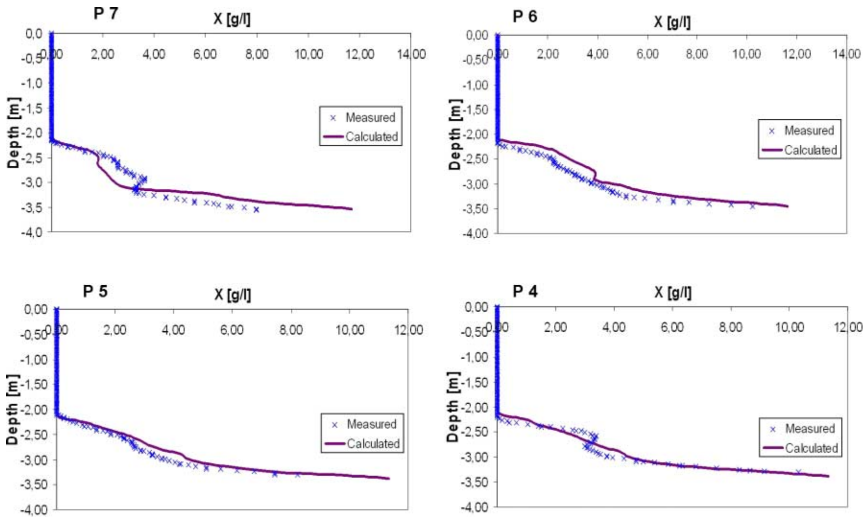

Figure 3 | Comparison of measured and calculated SS concentrations in representative vertical profiles of the SST.

During this first measurement period the SSTs at the WWTP of Graz received $Q = 800$ l/s (typical dry weather flow), with an average inflow SS concentration of 4.3 g/l. The return sludge flow was kept as constant at $Q_{RS} = 1{,}200$ l/s. As seen in Figure 3 reasonable agreement was obtained between measured and calculated concentrations, validating the modelling assumption and the applied settling function. As to other model parameters, standard constants of the k-ε turbulence closure and the default roughness height offered by FLUENT for smooth concrete surfaces were adopted.

A step toward analysing more complex system behaviour was the investigation of a 22 hours period with representative dynamic loading. Figure 4 presents the comparison of the measured and calculated time series for SS and return sludge concentrations. We note that during the measuring period the operating staff turned off twice the aeration in the aeration tank (at 12:00 and at 18:30) because of operational reasons. This led to sedimentation in the aeration tank resulting in the two negative peaks in the concentration time series (location 1 in Figure 4), which then resulted in further two negative peaks in the SS concentration time series of the return sludge (location 2 in Figure 4). Except these negative peaks, the simulated values, nevertheless, show an overall good agreement with the measured ones.

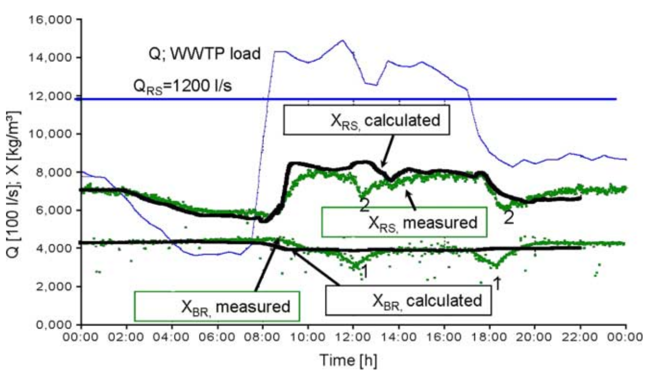

Figure 4 | Comparison of measured and calculated concentrations of return sludge and SS in the BR.

RESULTS AND DISCUSSION

The validated model was also used to investigate various scenarios representing extreme high load schemes. As a variant, a peak flow event was established by superimposing a realistic peak onto a typical daily load time series (Figure 5),

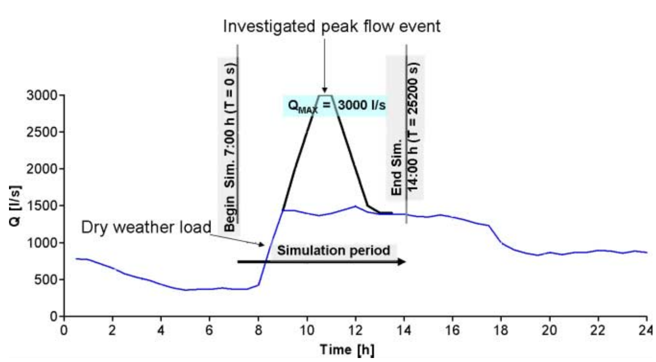

Figure 5 | Investigated peak flow scenario.

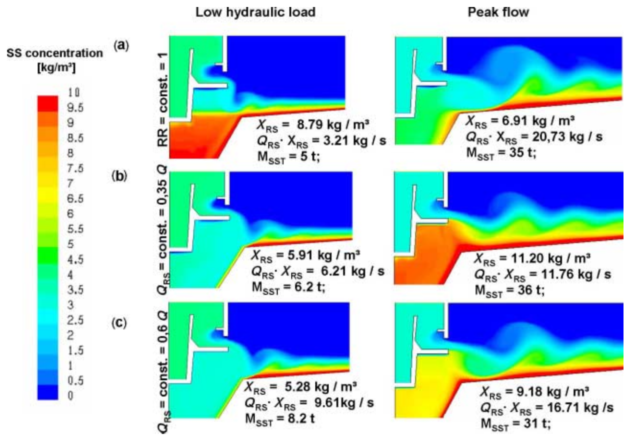

Figure 6 | Concentration pattern in the inlet zone of the SST (a) Return sludge flow adapted to the current load of the WWTP with a constant recycling Ratio ($RR = Q_{RS}/Q = $ const.); (b) Constant return sludge flow rate independent from the current load of the WWTP ($Q_{RS} = $ const.) with return sludge ratio of 0.35; (c) Return sludge ratio of 0.60. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwapublishing.com/wst.

obtained from the one seen in Figure 4 with slight smoothing. A time period from 7:00 to 14:00, covering the artificially enhanced load, was investigated.

Figure 6a shows the concentration pattern within the SST by a return sludge flow adapted to the current load of the WWTP with a constant recycling ratio ($RR = Q_{RS}/Q = 1$). Initially the low WWTP load at 7:00 results in low hydraulic load of the SST ($Q + Q_{RS}$) due to the adaptation mechanism. The resulting low flow velocities and low level turbulence (not shown here) in the SST provide efficient settling and thickening as well as favourably high return sludge concentration. However, the rapid increase of the WWTP load induces an undesirable, strong increase of the return sludge flow rate and SST load. The results are high velocities and turbulence level in the SST, thus disturbing the settling and thickening by eroding the thickening layer and diluting the return sludge.

The sludge mass in the SST before and during the peak flow event in case of an adapted return sludge flow and with various constant recycling ratios ($RR = Q_{RS}/Q = $ const) is shown in Figure 7a. The sludge mass transfer from the BR to the SST can be reasonably minimised by a return sludge ratio in the range of 0.6 up to 0.7. Return sludge ratios exceeding of 0.7 lead to a too high SST load resulting in increased flow velocities, high level turbulence and decreased settling and thickening performance as well as to low return sludge concentration. All this leads to an unfavourably high sludge transfer from the BR into the SST. Low return sludge flow rates accompanied with return sludge ratio less than 0.6 lead to an insufficient return sludge transport and to a high sludge mass transfer. The disadvantage of this sludge return strategy is the deterioration of the SST performance because of the large and rapid variation of the SST load, especially when moving from low to peak WWTP load at a speed to fast for the system for continuous adaptation.

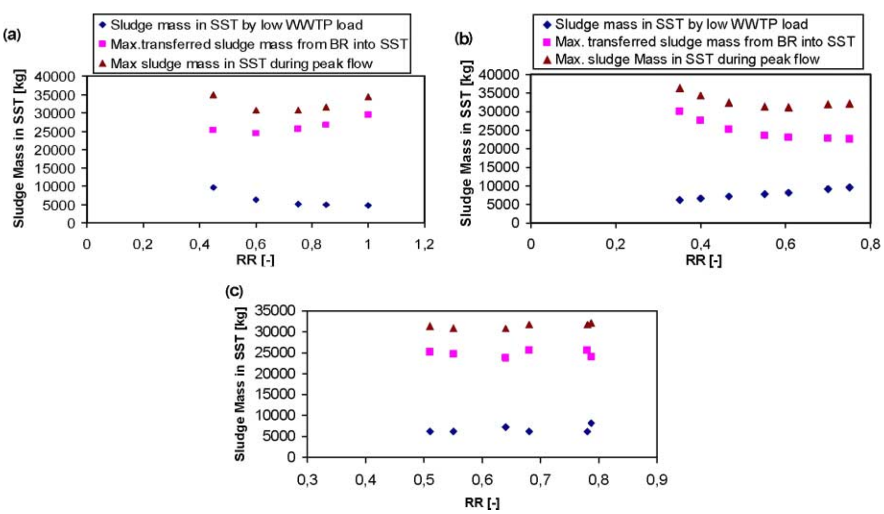

Figure 7 | Sludge mass in the SST at peak flow event. (a) Adaptation of the return sludge flow to the current load of the WWTP with a constant recycling ratio ($RR = Q_{RS}/Q = $ const.); (b) Constant return sludge flow rate independent from the current load of the WWTP ($Q_{RS} = $ const.); (c) Increasing the return sludge flow in a way proportional to the increase of the WWTP load, applied above a threshold inflow, and shifted in time.

The stabilised concentration pattern in the SST by the time the peak flow arrives as well as a typical snapshot of the concentration distribution developed in the dynamic peak flow simulation assuming constant low return sludge flow rate ($Q_{RS} = 0.35Q$) are shown in Figure 6b, displaying also the total instantaneous sludge mass in the SST. The same for high, though still constant return sludge flow rate ($Q_{RS} = 0.60Q$) is presented in Figure 6c. In case of maintaining a constant return sludge flow at low WWTP load (that is before the peak comes) a high return sludge flow rate is applied compared with the WWTP load. The relatively high return sludge flow rate enhances then the flow rates between the BR and SST, resulting in an enhanced sludge mass in the SST. Consequently, at low WWTP load the sludge mass in the SST increases linearly with increasing applied return sludge flow rates (Figure 7b).

Low return sludge flow rate applied with return sludge ratio less than 0.5 leads to high maximum sludge mass in the SST, however, in a highly consolidated form. In a range of the return sludge ratio between 0.5 and 0.7 the transferred sludge mass could be reasonably reduced. By applying a high return sludge flow rate with return sludge ratio more than 0.7 the increased SST load disturbs the settling and thickening processes. In this upper range of the return sludge flow rate the transferred sludge mass and thus the maximum sludge mass within the SST increases.

The results in case of increasing the return sludge flow rate in a way proportional to the increasing WWTP load once the latter is above a threshold inflow are is shown in Figure 7c. Favourable results regarding the transferred sludge mass and the maximum sludge mass in the SST could be reached compared to the other investigated sludge return strategies. In the investigated strategies the threshold of the inflow varied from 0.4 Q_{MAX} to 0.6 Q_{MAX}, the proportion of the increasing sludge flow rate from 30% to 60% following the increase of the WWTP load, and the time shift of the start of the sludge flow rate increase from 20 to 30 min.

CONCLUSIONS

In the paper a novel mass transport model of an activated sludge system was presented, which was able to reproduce the essential of the flow and mass transport processes within a conventional SST, also between the SST and the BR in unsteady, dynamic load conditions. The advantage of the presented mass transport model compared to former models is that it provides a 2-dimensional (axisymmetric) description of the processes in the SST making in such a way possible the detailed investigation of the effect of different sludge return strategies on the flow and concentration patterns, also the impact of other important factors (e.g. the tank geometry, especially it inflow region) on the efficiency of the sludge returning. The model has been validated for the WWTP of Graz. Simulating peak flow events measured in situ, the paper analyse and evaluates the basic differences between the various sludge return strategies used in common WWTP operation practice. The result of the investigations can be summarised as follows.

(1) A constantly low return sludge flow rate (Q_{RS} = const. and less than $0.5Q_{MAX}$) presents an insufficient sludge mass transport especially at peak flow event, resulting in high sludge mass in the SST. A constantly high return sludge flow rate brings in fact a sufficient sludge mass transport at peak flow events, but unfavourably high return sludge flow rate at low WWTP load.

(2) A return sludge flow rate adapted to the current load of the WWTP with constant recycling ratio ($RR = Q_{RS}/Q$ = const.) at low WWTP load results in low SST load, which quickly increases by the increase of the WWTP load and disturbs the settling and thickening by high flow velocities and turbulence level.

(3) For the reasons mentioned above the following sludge return strategy is recommended. The return sludge flow rate Q_{RS} should be kept at a constant value equal to $0.4Q_{MAX}$ at low WWTP load. With increasing WWTP load, once the inflow rate exceeds a threshold value equal to $0.5Q_{MAX}$ the return sludge flow rate should be slowly increased up to $0.6Q_{MAX}$. The increase of the return sludge flow rate should begin in a delayed manner, about 20 to 30 minutes after the threshold inflow rate is exceeded.

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