Analysis of suspended solids transport processes in primary settling tanks

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ABSTRACT

The paper shows the results of a long-term research comprising FLUENT-based numerical modeling, in situ measurements and laboratory tests to analyze suspended solids (SS) transport processes in primary settling tanks (PSTs). The investigated PST was one of the rectangular horizontal flow PSTs at a large municipal wastewater treatment plant (WWTP) of a capacity of 500,000 population equivalent. Many middle-sized and large WWTPs are equipped with such PSTs. The numerical PST model was calibrated and validated based on the results of comprehensive in situ flow and SS concentration measurements from low (5 m/h) up to quite high surface overflow rates of 9.5 and 13.0 m/h and on settling and other laboratory tests. The calibrated and validated PST model was also successfully used for evaluation of some slight modifications of the inlet geometry (removing lamellas, installing a flocculation ‘box’, shifting the inlet into a ‘bottom-near’ or into a ‘high’ position), which largely affect PST behavior and performance. The investigations provided detailed insight into the flow and SS transport processes within the investigated PST, which strongly contributes to hydrodynamically driven design and upgrading of PSTs.

Key words | activated sludge process, computational fluid dynamics (CFD), clarifier, light biodegradable carbon, settling velocity, wastewater treatment

INTRODUCTION

Primary settling tanks (PSTs) of large wastewater treatment plants (WWTPs) are essential both for wastewater treatment and renewable energy production using digester gas. With new technologies in wastewater treatment emerging over the last three decades, especially since biological nutrient removal has been required, their function and operation have become more complex.

In former times, the function of PSTs was to remove as high a rate of total suspended solids (SS) and organic carbon as possible in order to decrease SS load, aeration tank volumes, and aeration energy demands. This required PST design procedures and operation control which aimed at the maximum removal efficiency of SS and organic carbon. Instead of this, nowadays the design goals have turned into finding an optimum way of removal efficiency in order to ensure: (i) substrate for denitrification through organic carbon in primary clarified wastewater in order to achieve a satisfactory C/N ratio and a high rate of denitrification; and (ii) substrate for a satisfactory digester gas production via co-digestion of primary sludge (i.e. ATV-DVWK 2000; Metcalf & Eddy 2003; Gujer 2007; Somlyody & Patziger 2012). Therefore the function and operation of PSTs have become much more complex including the control of readily biodegradable carbon between denitrification and anaerobic digestion (biogas production) (Dulekgurgen et al. 2005; Alanya et al. 2012). This requires detailed investigations to substantially improve our knowledge on the hydraulic and removal processes within PSTs. While secondary settling tanks (SSTs) have received much attention over the last decades (e.g. Larsen 1977; Günthert 1984; Krebs 1991; Deininger et al. 1996; Patziger et al. 2005, 2012), behavior of PSTs has been poorly addressed.

Requirements for PST performance are strongly determined by the size of WWTPs, inflowing wastewater characteristics, effluent criteria, and the process of subsequent wastewater treatment and sludge stabilization. These requirements are strongly changing in time depending on factors described above and on further boundary conditions like temperature, primary sludge quality, etc. Thus
in addition to the design considering all these factors, a permanent process-driven operation control is needed.

The design procedures of PSTs currently used are still based on the Sierp and Greeley diagrams considering surface overflow rate \( q_s \) and hydraulic retention time (Hazen 1904; ATV-DVWK 2000, 2003; Metcalf & Eddy 2003). In these procedures dating back to earlier times, PSTs are still handled as a black box. Their facilities, geometry, operation, and further important features are poorly addressed. Design and operation are still based on empirical relationships. Essential physical processes, like non-homogeneous and anisotropic turbulence, flow pattern, and the direct way of describing SS transport and their interaction mechanism with settling and removal are rarely considered.

When investigating processes in PSTs, the following questions arise: (i) how do increasing surface overflow rates affect flow patterns and removal efficiency within PSTs, (ii) how is PST performance influenced by tank geometry features, (iii) what about the real removal behavior, performance, and efficiency of PSTs compared to design values used in practice, and finally (iv) how can approved design procedures and control strategies driven by boundary conditions contribute to a satisfactory PST function in modern wastewater treatment?

To answer all these questions long-term in situ investigations, laboratory tests, and computational fluid dynamics (CFD) simulations are needed.

Focused mainly on issues (i), (ii), and (iii), the present paper shows the outcome of long-term research. Results of numerical model investigations and a comprehensive in situ measuring campaign are given, providing a series of interesting details of PST behavior and contributing to better understanding of the complex process of primary settling.

\section*{MATERIALS AND METHODS}

\subsection*{Computational model}

Because in rectangular PSTs, the main flow and mass transport processes take place in the longitudinal direction, they can reasonably be investigated by a 2D approach (x-z plane) (Krebs 1991; Armbruster et al. 2001; Hunze 2005) that leads to shorter calculation times and smaller computer capacity needed.

The turbulent flow is modeled by the Reynolds-averaged Navier–Stokes equations with an RNG (re-normalization group) type of \( k-\varepsilon \) turbulence closure (Rodi 1980). Transport processes are described by an advection–diffusion equation with terms describing settling and thickening in which special settling, density, and rheology modules were implemented. Density and viscosity features of sludge are considered as a function of the local SS concentration (Casey type of approach; Casey 1992).

In a Casey-type approach (1), the sludge suspension is represented as a pseudo-plastic fluid by

\[ \Theta = \Theta_0 + K \left( \frac{du}{dy} \right)^N, \]

where \( \Theta \) is shear stress, \( \Theta \) is yield shear stress, \( K \) is consistency coefficient, and \( N \) is consistency index.

A series of state-of-the-art reviews on sludge rheology (Mori et al. 2006; Eshtiaghi et al. 2013; Ratkovich et al. 2013) clearly state that sludge has a Newtonian behavior in the range of low SS concentrations up to 6–8 g/L. Settled and thickened sludge (above this range) is always non-Newtonian.

Settling velocity is described as a function of the local concentration, which is a novel approach in the case of modeling PSTs. The latter is presented in the subsequent section in more detail. The governing equations are numerically solved by the CFD code ANSYS FLUENT 14.5 by means of an implicit unsteady segregated solver on a boundary-fitted finite volume grid.

\subsection*{Calibration and verification}

The measurement campaign was carried out at the Graz municipal wastewater treatment plant, which has a capacity of 500,000 population equivalent (PE) and 90,000 m\(^3\)/d as well as a peak capacity of 1,600 L/s (dry weather) and 3,200 L/s (wet weather).

One of the four rectangular PSTs of the plant was investigated (Figure 1(a)–(c)). The inflowing wastewater is divided between the tanks by quite a complicated distributor facility (Figure 1(b)).

The tanks are 32.50 m long, 7.00 m wide, and 3.95 m deep on average. They are loaded at their front side, where also the sludge hoppers are situated. The inlet structure is characterized by inlets positioned high above the bottom near the water surface, behind lamellas (Figure 1(c)). The latter are meant to dissipate the inflowing jet's kinetic energy. The bottom is slightly sloped and the settled sludge is carried by a scraper toward the sludge hoppers at a speed of less than 2 cm/s, so as not to disturb the settling and thickening process within the tank. The primary clarified wastewater leaves the tank through effluent weirs at the rear.

For investigating the hydrodynamic behavior, a measuring method developed and successfully used for the analysis of SSTs (Patziger et al. 2005, 2012) was adapted.
The flow pattern was investigated by a high-tech acoustic Doppler current meter ‘Nortek Vector’, which is able to detect very low velocities and turbulence features even in the range of millimetres per second. The instrument was installed at the scraper bridge. The scraper was distinctly operated in every cross-section (A, B, C, D, and E indicated in Figure 2) during the measurements.

The inflowing and outflowing SS concentrations were continuously measured and registered by an optical turbidity meter (Solitax ts-line sc) equipped with two sensors, positioned at the inflow and in the outflow (dots 1 and 2 in Figure 1(b)). The turbidity meter was calibrated by laboratory tests. To calculate SS load, the inflow measurement data of the PST were used. To avoid uncertainties due to the probably non-equal load of the four PSTs, also in situ inflow measurements were carried out in the section 1 (open-flow channel), supplying the investigated PST (Figure 1(b)). For these complementary inflow measurements (every 15 min of each measuring campaign), an ‘OTS Nautilus’ type of electromagnetic current meter was used.

The measurements were carried out at three overflow rates (5.0, 9.5, and 13 m/h); the latter two were definitely higher than the one recommended by the German design guidelines ATV-DVWK-A 131 (ATV DVWK 2000), in order to investigate tank performance also at such an extremely high hydraulic load.

To justify the 2D model approach, the measured longitudinal (direction of the tank length /x-z plane/) and transversal (direction of the tank width /x-y plane/) velocity components were compared to each other. Owing to the tank geometry (nearly uniform inflow and uniform outflow along the hall tank width), the longitudinal velocity profiles in the measuring verticals of the indicated planes (Figure 2, A-A sections 1–4) showed a very similar pattern. The magnitude of transversal velocity components of 0–1 cm/s (x-y plane) is negligible compared to the longitudinal ones (x-z plane), which ranged about 3–20 cm/s. Neither large-scale horizontal (x-y plane) structures nor dead zones could be observed in the tank corners. In the case of the investigated PST only special investigations, for example internal details of inlet facilities, near-field flow pattern of scraper, local pattern around removal system, would require 3D model investigations.

In common praxis, Stokes’ law has been widely used for describing settling of particles in PSTs. However settling functions describing settling velocity as function of the local concentration could provide a more accurate approach for settling and thickening properties of primary sludge.

To investigate settling properties of primary sludge, settling tests were carried out in 1.94 m high cylinders with a diameter of 0.30 m to avoid undesirable wall effects (Krebs 1991; Gong et al. 2011). During the measurements, also video motion analysis was used to evaluate settling velocities especially in the low range of SS concentrations (far below 1 g/L). These resulted in a settling curve for primary sludge shown in Figure 3 (dots). To obtain a satisfactory amount of settling velocity data, further complementary measurements were carried out also at the Central Budapest WWTP (1,300,000 PE). The results obtained from the different measurement campaigns show a very close agreement to each other.

Figure 1 | Bird’s-eye view (a), layout (b), and inlet facility (c) of the investigated PST.
Figure 2 | Longitudinal and cross-section of the investigated PST with the applied measuring raster.

Figure 3 | Settling function.
In comparison to the settling behavior of activated sludge, it was found that primary sludge particles have much higher maximal settling velocities (about 10–11 cm/s) especially in a low range of SS concentrations of about 100–200 mg/L (0.1–0.2 g/L) due to their higher relative density and larger initial particle diameter (a range from 0.01 mm to even 0.2–0.5 mm was measured using video screenshot analysis). Activated sludge flocs only reach this range of settling velocities after a satisfying rate of flocculation at far higher SS concentrations of about 1 g/L (1,000 mg/L) in the zone-settling phase.

Based on the measurements, a settling function was set (Figure 3 – continuous line), which consists of four parts similar in shape to that of Takács et al. (1991) originally established for activated sludge. Phase 1 describes the non-settleable solids, where the settling velocity equals practically zero. Instead of formulating the settling function as the sum of two exponential terms, as a simplified solution, a linear function describes the settling velocities in the range of the low total suspended solids (TSS) concentrations (phase 2 – flocculation phase) whereas a constant one describes the range of the highest measured settling velocities (phase 3 – zone settling).

Finally, the settling velocities in the measured range at higher SS concentrations (phase 4 – hindered settling, thickening) are approximated by an exponential function as usual (Vesilind 1968; Takács et al. 1991; Patziger et al. 2012), showing a reasonable fit to the measured values (indicated by dots).

**RESULTS**

The simulation results are compared with the full-scale measured horizontal velocity profiles, flow patterns, and inflow and effluent SS concentrations. In Figures 4 and 5, the predictions of the CFD model developed using the new settling velocity model of primary sludge show an

![Figure 4](https://example.com/fig4.png)

**Figure 4** | Comparison of measured and calculated velocities at 9.5 m/h in the measuring profiles.
overall close agreement with the measured profiles, particularly the flow pattern and effluent concentrations (Figure 5).

The main function of the inlet facility is the dissipation of both the kinetic and potential energy of the inlet jet, and furthermore to ensure a nearly uniform flow field, which is necessary for an efficient PST performance. In satisfying operating PSTs, the inlet must ensure a uniform flow pattern through a minimum recirculation zone, avoiding high turbulence and dead zones (Józsa & Krámer 2000).

However, the investigated PST shows an unfavorable pattern. As visible in Figure 5, the inlet jet plunges with a considerable downward momentum component facilitated by lamellas positioned outside the inlet facility directly in the settling zone. The flow pattern is strongly affected by high-velocity components induced by the inlet construction (too low hydraulic retention time, lamellas), and furthermore by the developing jet along the tank. This clearly shows that the inlet jet’s kinetic and potential energy has to be satisfactorily dissipated within the inlet facility, which requires a design strongly based on hydrodynamic principles (satisfactory volume and hydraulic retention time as well as optimal geometry design and inlet height).

Owing to the higher ranges of velocity magnitude, the lower SS concentrations and much lower sludge mass stored in PSTs than in SSTs, the flow and transport processes of the already settled and thickened sludge mass do not affect the flow pattern considerably. Therefore, strong density effects in PSTs like ‘density waterfall’ (Krebs 1991; Patziger et al. 2005) in the inlet zone and density currents within the settling zone can be neglected.

Generally, the flow pattern is characterized by very high velocities (at higher overflow rates far above 10–15 cm/s at the inlet) and a large recirculation region spanning a large part of the tank from top to bottom (Rostami et al. 2011). This recirculation zone increases with increasing surface overflow rates, deteriorating PST efficiency by leading to high turbulences, short-circuiting (Günthert 1984), and even to resuspension of settled sludge particularly in the near-field zone of the sludge hopper. Consequently, disturbing of settled sludge and insufficient transport toward sludge hoppers result in low raw sludge concentrations and in overloading of the sludge treatment facilities.

The calibrated and validated PST model was also successfully used for evaluation of some slight modifications of the inlet geometry (removing lamellas, installing a flocculation ‘box’, shifting the inlet into a ‘bottom-near’ or into a ‘high’ position) largely influencing PST behavior and performance. The investigations were carried out at a quite high surface overflow rate of 9.5 m/h.

As a result of removing the lamellas, the regions with large circulations in the inlet near field (Figure 6(a)) can be avoided (Figure 6(b)), but a jet with high horizontal velocity components develops, drifting the settled sludge toward the outlet, strongly affecting PST performance at such high hydraulic load. Despite installing a flocculation box, to decrease kinetic energy of inflowing wastewater, this
undesirable pattern becomes even worse by shifting the inlet into a bottom-near position (Figure 6(c)). A reasonably higher PST performance (TSS removal >50%, sevenfold increased average TSS concentration within the sludge hopper) can be achieved by installing a flocculation box and shifting the inlet in a ‘high’ position into that layer, where the range of SS concentrations approximately equals the inflowing jet’s SS concentration (Figure 6(d)). This results in a minimum of kinetic energy in the tank leading to a more favorable flow and concentration pattern with considerably enhanced SS concentrations within the bottom-near layers and within the sludge hopper. This leads furthermore to a slightly enhanced SS removal efficiency compared to the original geometry.

SUMMARY

In the paper, the results of a numerical model study of a rectangular PST are presented.

A 2D numerical PST model considering all of the important physical processes, the inhomogeneous turbulent flow, mass transport, settling, and thickening was developed.
The model was calibrated and validated based on the results of comprehensive in situ flow and SS concentration measurements from low (5 m/h) up to quite high surface overflow rates of 9.5 and 13.0 m/h as well as settling and other laboratory tests. The flow pattern was investigated by a high-tech acoustic Doppler current meter (NORTEK VEKTOR). The continuous on-line measurement of the inflowing and outflowing total SS concentration was carried out by an optical turbidity meter (Solitax ts-line sc).

As a novel approach to include primary sludge settling properties within a CFD model, the same mathematical method was adapted, which is widely used in the case of modeling SSTs. A settling function describing settling velocity of primary sludge as the function of the local concentration was established, which was fitted to measured values obtained from a huge amount of settling tests carried out with primary sludge.

The methodology could successfully be applied, providing an overall close agreement between calculation and measurements.

The calibrated and validated PST model was successfully used for evaluation of the investigated PST and of some slight modifications of the inlet geometry, which largely influences PST behavior and performance.

In PSTs density effects like ‘density waterfall’ in the inlet zone and density currents within the settling zone can be neglected; however, in the inlet zone extraordinary high-velocity components could be observed. These resulted in large circulation and dead zones, decreasing PST performance. This was due to inappropriate geometry design of the inlet facility, leading to insufficient energy dissipation.

In the case of shifting the inlet in a ‘bottom-near’ layer, a jet with extraordinary high horizontal velocity components develops, drifting the settled sludge toward the outlet, strongly affecting PST performance especially at high hydraulic loads.

A reasonably higher PST performance (TSS removal >50%, seven-fold increased average TSS concentration within the sludge hopper) can be achieved by installing a flocculation box and shifting the inlet in a ‘high’ position into that layer, where the range of SS concentrations approximately equals the inflowing jet’s SS concentration.

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