On the design and operation of primary settling tanks in state of the art wastewater treatment and water resources recovery

Miklos Patziger, Frank Wolfgang Günthert, Norbert Jardin, Harald Kainz and Jörg Londong

ABSTRACT

In state of the art wastewater treatment, primary settling tanks (PSTs) are considered as an integral part of the biological wastewater and sludge treatment process, as well as of the biogas and electric energy production. Consequently they strongly influence the efficiency of the entire wastewater treatment plant. However, in the last decades the inner physical processes of PSTs, largely determining their efficiency, have been poorly addressed. In common practice PSTs are still solely designed and operated based on the surface overflow rate and the hydraulic retention time (HRT) as a black box. The paper shows the results of a comprehensive investigation programme, including 16 PSTs. Their removal efficiency and inner physical processes (like the settling process of primary sludge), internal flow structures within PSTs and their impact on performance were investigated. The results show that: (1) the removal rates of PSTs are generally often underestimated in current design guidelines, (2) the removal rate of different PSTs shows a strongly fluctuating pattern even in the same range of the HRT, and (3) inlet design of PSTs becomes highly relevant in the removal efficiency at rather high surface overflow rates, above 5 m/h, which is the upper design limit of PSTs for dry weather load.

Key words | biodegradable carbon, computational fluid dynamics, DWA, primary settling tanks, suspended solids, wastewater treatment

LIST OF ABBREVIATIONS

BNR Biological nitrogen removal
CFD Computational fluid dynamics
COD Chemical oxygen demand
DWA German Association for Water, Wastewater and Waste
HRT Hydraulic retention time
PE Population equivalence
PST Primary settling tank
SS Suspended solids
SST Secondary settling tank
TKE Turbulent kinetic energy
TN Total nitrogen
TP Total phosphorus
WWTP Wastewater treatment plant

INTRODUCTION

Primary settling tanks (PSTs) are an integral part of the entire wastewater treatment process, sludge treatment and digester gas production. With new developments emerging in wastewater and sludge treatment over the last three decades, especially since biological nutrient removal has been required, their function and operation has become complex, controlling readily biodegradable carbon between anaerobic digestion with digester gas production and biological nitrogen removal (BNR) (Appendix 1, Table 1, available with the online version of this paper).

The design procedures of PSTs currently used are still based on the Sierp and Greeley diagrams considering surface overflow rate ($q_A$) and hydraulic retention time (HRT) (Hazen 1904; ATV DVWK 2000, 2003; Metcalf & Eddy Inc. 2003). In these procedures dating back to...
earlier times, when no BNR was required, 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 suspended solids (SS) transport and their interaction mechanism with settling and removal are rarely considered. The systematic investigation of PSTs has rarely been addressed in the last decades.

Optimizing the removal of particulate organic matter will increase gas production in anaerobic digesters but excessive removal will deprive the BNR process of carbon for biological nitrogen and phosphorus removal. It allows the energy generation of the plant to be optimized by removing as much particulate chemical oxygen demand (COD) in the PST as possible without impairing the BNR. Approved design procedures and boundary condition driven control strategies (capacity used, scraper mechanism, sludge removal) are to be developed, which can contribute to a satisfactory PST function. It is always possible to ferment a fraction of the primary sludge to produce just enough carbon for the BNR process (Alanya et al. 2012).

Rostami et al. (2011) showed, using a two-dimensional (2D) computational fluid dynamics (CFD) model, some important hydrodynamic processes in PSTs and possibilities of enhancing PST performance. The CFD model they used was calibrated and validated against pilot scale measurements and did not include SS transport, thus neglecting interaction between SS transport and flow processes.

This paper presents a further step towards improved design procedures and boundary condition driven control strategies. A comprehensive investigation programme was carried out including 16 PSTs, four of which were wastewater treatment plants (WWTPs) with a capacity of around 1 million population equivalence (PE). Removal efficiency, settling properties of primary sludge, internal flow structures within PSTs and their impact on performance were investigated and evaluated.

Questions to be answered were: (i) how current design principles fit the real behaviour and performance of PSTs at large WWTPs, (ii) how geometry design (especially inlet design: inlet height) affects PST performance considering a wide range of load conditions from average dry weather conditions up to heavy storm flow, and (iii) which general improvements should be set in the design process and operation of PSTs.

MATERIALS AND METHODS

The investigation programme consisted of three tasks: (1) a full scale measurement programme on 12 German WWTPs, (2) a data evaluation of four large WWTPs with a capacity of about 1 million PE, and (3) a CFD study of a rectangular PST widely applied at large WWTPs. The detailed methodology of these tasks is given as follows.

(1) A measurement programme was initiated among large WWTP operators in Germany, in order to estimate the performance of full scale PSTs. Within this measurement campaign the load of COD, particulate COD (XCOD), SS, total nitrogen (TN) and total phosphorus (TP) were determined in the influent and effluent of the full scale plants on the basis of flow proportional 24-h composite samples. For every single plant at least five dry weather days were included in the calculation of the performance indicators. Also, on some of these plants excess sludge or sludge water is usually added to the influent of the PST. These additional flows were stopped during the course of the measurement. The HRT has been calculated based on the volume of the PST and the daily flow rate during the measurement period.

(2) A further data evaluation of PSTs was carried out including large WWTPs with a capacity of around 1 million PE. The evaluation of these data was part of a comprehensive research project in which the efficiency of the new Budapest Central WWTP (full capacity: 1.666 million PE, average load 1.185 million PE) was analyzed. The inflowing and outflowing data series of the PSTs were evaluated based on a long term data series (from 2010 to 2015). The data were compared to three other large German WWTPs with approximately the same capacity, all of them operating based on the activated sludge process (WWTP ‘A’ 0.947 million PE, WWTP ‘B’ 0.994 million PE and WWTP ‘C’ 1.003 million PE).

(3) To investigate the geometry design and its impact on removal efficiency a series of CFD simulations were carried out. For this purpose, a FLUENT-based PST model was developed, largely utilising the model settings of Patziger & Kiss (2015). The model was calibrated and validated against fine-scale in situ measurements (acoustic Doppler velocimetry, optical turbidity meter) and settling tests. The 2D PST model solves the Reynolds-averaged Navier-Stokes equations with a ‘renormalization group k-ε’ type of turbulence closure with its standard parameters \( c_{1t} = 1.42 \), \( c_{1t} = 1.68 \). Transport processes are described by the advection–diffusion

\[ \frac{\partial c}{\partial t} + \nabla \cdot (\vec{u} c) = \nabla \cdot \left( \kappa \nabla c \right) + S_c \]

where \( \kappa \) is the diffusion coefficient, \( S_c \) is the source term, and \( \vec{u} \) is the velocity field.
including a term for a novel type of settling function (Equation (1)). The settling function giving the settling velocity of primary sludge as a function of the local SS concentration was established based on data obtained from in situ settling tests. The latter is the main calibration (adjustable) parameter of the PST model and has to be calibrated at each PST against in-situ measurements (acoustic-Doppler velocimetry and optical turbidity measurements). Other parameters of the equations are assumed with their default values. Density and viscosity features of sludge are also considered as a function of the local SS concentration:

\[ v_s = 0 \quad \text{for} \quad (0 < X < 0.025 \, \text{g/l}) \]  
\[ v_s = 3.6X - 0.09 \quad \text{for} \quad (0.025 < X < 0.050 \, \text{kg/m}^3) \]  
\[ v_s = 0.09 \quad \text{for} \quad (0.050 < X < 0.080 \, \text{kg/m}^3) \]  
\[ v_s = 0.167 \cdot e^{-0.008X} \quad \text{for} \quad (0.080 \, \text{g/l} < \text{kg/m}^3) \]

where \( v_s \) is settling velocity (cm/s) and \( X \) is local SS concentration (kg/m\(^3\)).

Density and viscosity features of sludge are also considered as a function of the local SS concentration (Casey 1992; Mori et al. 2006; Eshtiaghi et al. 2013; Ratkovich et al. 2013).

The investigated tank was one of the four rectangular PSTs of the Graz Municipal WWTP (design inflow data: 90,000 m\(^3\)/d, 30,000 kgBOD\(_5\)/d, 60,000 kgCOD/d, 4,750 kg TKN/d, 750 kg P/d). It is 32.50 m long, 7.00 m wide and 3.50 m deep (loaded at the front side; high inlet position with vertical lamellas at the inlet originally meant to dissipate the kinetic energy of the jet entering the tank; effluent weir at the rear-side).

The governing equations are numerically solved by the CFD code FLUENT 14 by means of an implicit unsteady segregated solver on a boundary-fitted orthogonal finite volume grid, with a nearly uniform cell size of 0.05 x 0.05 m. The grid was generated based on the Courant criterion. The grid consists of 31,753 nodes (Figure 1(a)). This enables a fine enough resolution at locations with high gradients (especially inlet, outflow, highly turbulent regions) and in the wall-near-layers.

The model was calibrated and validated at the investigated PST at three different overflow rates: \( q_A = 5 \), 9.5 and 13 m/h (Patziger & Kiss 2015). Figure 1(b) shows the results of the calibration and validation at the surface overflow rate of 9.5 m/h (wet weather flow). The predictions of the CFD model show an overall close agreement. The comparison of measured and calculated effluent SS concentrations are given as follows \( q_A\) [m/h] range measured/calculated effluent SS concentrations: 5 m/h: 172–184/180 mg/l, 9.5 m/h: 200–208/204 mg/l, 13 m/h: 204–216/212 mg/l.

**RESULTS**

Figure 2 shows the results of these measurements concerning the elimination of SS and particulate COD at German large WWTPs, respectively.

The removal rates of SS and COD show an extraordinary fluctuating pattern. Even PSTs with the same HRT have completely different removal efficiencies, with deviations of up to 20–25% being observed. The removal efficiency of PSTs is obviously dependent on many other factors besides parameters determined by PST size and inflow conditions, like surface overflow rate and HRT (Figure 2(a) and 2(b)). The removal rates of COD are often distinctly higher than recommended by the current design guidelines. The measured removal rates of COD surpass design values (Sierp diagram and ATV A 131-ATV (ATV DVWK 2000)) by about 20–25%.

This pattern also can be confirmed based on the comparison of large PSTs of WWTPs with a capacity of around 1 million PE shown in Figure 3. A further outcome of this investigation is that the removal efficiency of other wastewater parameters, like TN and TP, show considerable fluctuations (COD 31%, SS 34%, TN 9%, TP 30% seen in Figure 3(c)).

Using CFD to investigate how inlet geometry design affects these results provides interesting findings.

In the case of the original inlet facility (Figure 4 – type I) with the lamellas, after entering the PST, the inlet jet turns downward due to the lamellas positioned directly at the inlet. The inlet velocities vary from 0.10 up to 0.20 m/s, which are strongly increasing with increasing surface overflow rate. These vertical velocity components become unfavourably high above a surface overflow rate of 5 m/h, which is the upper design limit for dry weather load. At high surface overflow rates (8 and 10 m/h) often caused by storm flow, the flow pattern is characterized by high velocities (far above 0.20–0.30 m/s at the inlet). A large recirculation region spans a large part of the tank from top to bottom. 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.

Due to the inflow SS concentrations and much lower sludge mass stored in PSTs than in secondary settling tanks (SSTs), the flow and transport processes of the already settled and thickened sludge mass do not affect the flow pattern significantly. Therefore, density effects in PSTs like ‘density waterfall’ (Krebs 1991) in the inlet zone and density currents within the settling zone do not dominate the flow pattern. The high kinetic energy induces a jet moving toward the outer boundary of the tank. The mean velocity of the jet (0.05–0.1 m/s) is much higher than the average values within the PST (0.01–0.02 m/s). Due to the slope of the base and the scraper mechanism the settled and thickened sludge moves towards the sludge hopper.

In the case of a high-positioned inlet facility equipped with an energy dissipating box (Figure 4 – type II) the flow pattern becomes more favourable. The kinetic energy of the inlet jet can be considerably decreased before entering the tank. This leads to a more uniform flow pattern without disturbing the settling and thickening process, resulting in a very good layering of settled sludge.

In the case of a deep-positioned inlet facility recommended for SSTs, the flow pattern and sludge layering are quite favourable up to a surface overflow rate of 5 m/h. At higher surface overflow rates such an inlet geometry
Figure 2 | (a) SS elimination in PSTs on full scale plants; (b) elimination of particulate COD in PSTs on full scale plants.

Figure 3 | Removal efficiency of PSTs (daily averages – grey dots (blue dots in online version)) at large WWTPs around 1 million PE. The full colour version of this figure is available online: http://dx.doi.org/10.2166/wst.2016.349.
Figure 4 | Influence of inlet geometry on flow, turbulence and concentration pattern in PSTs; v is velocity, TKE is turbulent kinetic energy and SS is suspended solids concentration.
leads to unacceptably high velocities in the base-near field, a stirring of the sludge bed, a wavy sludge–water interface and washing-out of settled sludge.

**DISCUSSION**

Considering the fluctuating results of the measurements on different large scale WWTPs, for an optimal integration of the primary clarification in the whole wastewater treatment design process, measurements to determine the performance of PSTs should be mandatory. For this purpose measurements should take place whenever possible. During such a measurement programme, proportional 24-hour composite samples in the influent and effluent should be analysed with respect to COD, SS, TN and TP. The duration of such a measurement programme should be longer than 1 week. By calculating the load in the influent and effluent of the PST, the elimination rate with regard to SS, particulate COD and the nutrients (TN, TP) can be easily assessed. Care has to be taken so that no internal process streams (e.g. sludge water from the dewatering or excess sludge), are directed to the PST during the measurement programme.

Only in design cases where no full scale results can be obtained (e.g. new plant or new PST) should the design estimates as summarised in Appendix 1 (Table 2) (available with the online version of this paper) be used. These performance indicators provide estimates to calculate the elimination of total COD, XCOD, SS, TN and TP.

The simulation results (Figure 5) show that the impact of the inlet geometry design becomes particularly relevant at surface overflow rates above 5 m/h, which is the upper design limit for dry weather conditions according to the German design guidelines (ATV DVWK 2000; DWA 2016) (Figure 5). At lower surface overflow rates than 5 m/h the inlet design does not affect PST performance significantly. Neither is there any significant difference in the performance of the investigated PST caused by different design of inlet geometry (type I – original, type II and type III). The results in Figure 5 also show the same pattern. The deviation of the average values of the velocity magnitude the turbulent kinetic energy, the effluent SS concentration and the SS removal efficiency are negligible at 5 m/h.

However at high hydraulic loads \( q_A = 8 \) and 10 m/h – wet weather conditions) slight modifications of the inlet geometry, such as installing an ‘energy dissipating box’, shifting

![Figure 5](http://iwaponline.com/wst/article-pdf/74/9/2060/457532/wst074092060.pdf)
the inlet into a ‘base-near’ or into a ‘high’ position, strongly affect PST behaviour and performance. For example, at a surface overflow rate of 10 m/h deviations up to 26% (0.3) could be observed by means of the CFD investigations (Figure 5(d)).

Consequently, especially in the design of PSTs usually operating at high surface overflow rates (retention times less than 0.5–0.75 h and surface overflow rates higher than 5 m/h), CFD investigations are recommended.

CONCLUSIONS

The paper presents the results of a comprehensive investigation programme on the design and operation of PSTs. Removal efficiency, settling properties of primary sludge, internal flow structures within PSTs and their impact on performance were investigated and evaluated. To investigate the inlet design and its impact on removal efficiency, also a series of CFD simulations were carried out. For this purpose, a FLUENT-based PST model including density and viscosity settling features of primary sludge was developed. The model was calibrated and validated against in situ measurements.

The results can be summarized as follows.

The removal rates of total SS, COD, TN and TP often surpass design values and show an extraordinary fluctuating pattern. Even PSTs with the same HRT have completely different removal efficiencies, with deviations up to $\Delta = 20–25\%$.

The impact of the inlet geometry design becomes particularly relevant at high surface overflow rates above 5 m/h. At surface overflow rates lower than 5 m/h the inlet design does not affect PST performance significantly. The deviations in flow pattern and removal efficiency caused by the modification of the inlet geometry are negligible.

However at high hydraulic loads ($q_A = 8$ and 10 m/h – wet weather conditions) the inlet geometry strongly influences PST efficiency, resulting in huge deviations in removal rates. In the case of the investigated rectangular PST, an optimized inlet geometry (high-positioned inlet with energy dissipating box), resulted in a reasonably enhanced SS removal efficiency (up to 26–45% improvement at a surface overflow rate of 10 m/h).

For an optimal design and boundary condition driven operation of PSTs in the whole wastewater treatment design process, on-line measurements in order to continuously observe the PST performance should be mandatory. Only in design cases where no full scale results can be obtained (e.g. new plant or new PST) should the design estimates be used. It is especially important that the design of PSTs usually operating at high surface overflow rates (retention times less than 0.5–0.75 h and surface overflow rates higher than 5 m/h) should be supported by CFD investigations.

REFERENCES


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