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Computational fluid dynamics investigation of shallow circular secondary settling tanks: Inlet geometry and performance indicators

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ABSTRACT

The paper presents the results of a long-term research program on the improvement of existing shallow circular secondary settling tanks (SSTs) based on the computational fluid dynamics (CFD) investigation of their inner hydrodynamic processes.

The results provide insight into the flow and concentration pattern within such SSTs and highlight some important details that largely determine their performance.

As a novel detail of the research of SSTs, a direct dependence was found between the inlet height and the length of the radial density jet induced by the entering water–sludge suspension. A hydrodynamically optimized (low positioned) inlet facility decreases the kinetic energy and the length of the density jet, as a result of which it vanishes before hitting outer boundary of the SST. This results in an enhanced performance indicators even of such shallow SSTs, under both dry weather and peak load conditions as well.

1. Introduction

The importance of inlet design of secondary settling tanks (SSTs) has been highlighted in a number of scientific works in the last years. This paper shows the results of a comprehensive investigation of an old shallow circular SST. Such kinds of SSTs are very frequently used throughout Europe and many other parts of the world. Most of them are characterized by operational problems. The most important of these problems is washing out of sludge, which directly leads to a decreased effluent quality especially under peak load conditions (wet weather conditions, storm events). This paper presents an investigation program, how their performance can be enhanced by slight modifications keeping their performance in an acceptable range even under peak flow conditions. In order to enhance SST performance, the improvement of the inner hydrodynamic behavior is the most essential issue. The hydrodynamic processes in SSTs are mainly depending on the features of the inner density currents occurring large scale flow structures. Though in SSTs the density difference between the inflowing sludge–water suspension and the medium within the tank is quite low (1–3%), it exerts a great influence on the flow pattern of a SST shown in Fig. 1 (Larsen, 1977; Günthert, 1984; Kainz, 1991; Krebs, 1991; Freimann, 1999; de Clercq, 2003; Patziger et al., 2005; Gong et al., 2011). Especially the inlet-near hydrodynamic processes are strongly influencing the entire flow pattern within SSTs. After entering the SST, the inlet jet turns downward due to its slightly higher density compared to the ambient fluid. Consequently large downward velocity components arise (1) in the inlet near field. The huge kinetic energy and the radial density gradient induce a density current (2) moving radially toward the outer boundary of the tank. The mean velocity of the jet (0.03–0.1 m/s) is much higher than the average values within the SST (0.01–0.02 m/s). Due to the mass conservation a counter flow (3) is induced in the upper zone of the SST, therefore a large scale radial circulation is evolving. Due to the slope of the base and the scraper mechanism the settled

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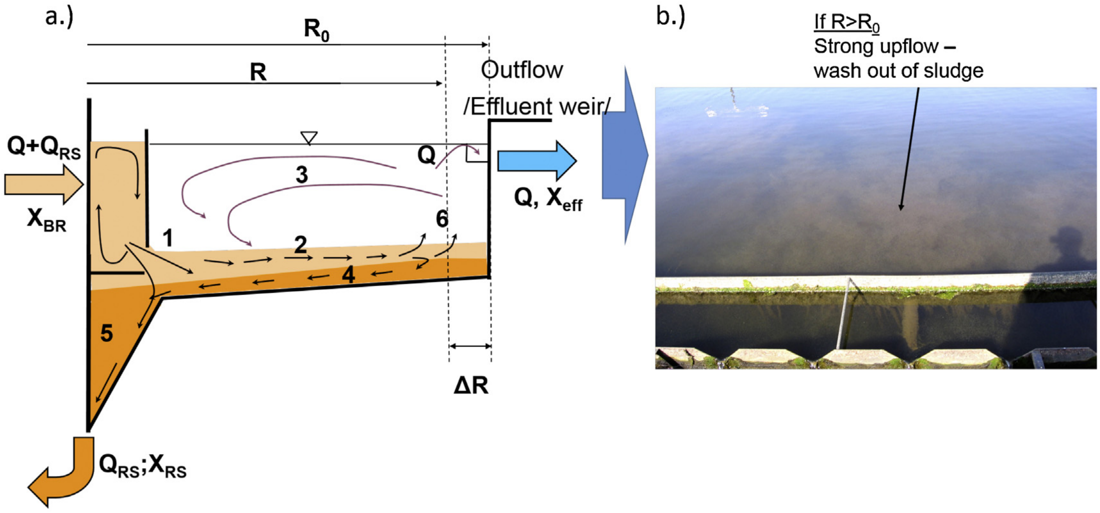

Fig. 1 – Typical physical processes in a circular secondary settling tank (R_0 – tank radius, R – radius/length of the radial density current, Q – inflow, Q_R – return sludge flow, X_{BR} – suspended solids concentration within the bioreactor/inflow suspended solids concentration, X_{eff} – effluent suspended solids concentration).

and thickened sludge (4) moves toward the sludge hopper (5) and is then returned into the aeration tank. In case of peak flow conditions due usually to storm events, the SST's performance becomes a very important issue in the effectiveness of the treatment plant. Peak flow events lead to a high hydraulic load of WWTPs inducing high inlet velocities and bringing increased sludge mass into the SST, all requiring operation at full capacity.

By lower surface overflow rates (q_A [m/h]) than a certain critical surface overflow rate (critical load – q_{crit}) the density current (2) vanishes before hitting the outer wall of the SST ($R/R_0 < 1$).

Once the hydraulic load exceeds the critical overflow rate (q_{crit}), the density current hits the outer wall of the SST ($R/R_0 > 1$) and a pronounced radial circulation in the vertical plan develops. This occurs high upward velocity components directly at the effluent (6) causing abruptly increasing effluent SS concentrations (Patziger et al., 2012).

In this paper the influence of the inlet design on this pattern is investigated. Following questions are to be answered: (1) How does the inlet geometry effects flow and concentration pattern, especially the length of the density jet and the large scale circulation moving radially toward the outer wall of the SST? (2) How much can the SST performance indicators (R/R_0 ratio, return sludge concentration, stored sludge mass in the SST and effluent WW quality) be enhanced by an appropriate modification of the inlet geometry. This is especially important under wet weather conditions, when hydraulic load reaches or even exceeds the existing tank capacity (critical hydraulic load).

2. Materials and methods

2.1. *The numerical model*

To answer these questions a CFD model was developed, calibrated and validated against a huge number of in situ measurements at the SSTs of the Graz Municipal WWTP. This approach enables the investigation of the issues mentioned above and provides a detailed insight into the complex flow and transport processes in the SST under of steady state and dynamic load conditions as well.

In circular SSTs the dominant hydrodynamic processes take place in the vertical plane (radial direction). Therefore they can reasonably be investigated by an axisymmetric approach. This kind of approach largely reduces the cell number, calculation time and required computer capacity without deteriorating the accuracy of the simulation compared to 3D simulations (Krebs, 1991; Armbruster et al., 2001; Bürger et al., 2011; Hunze, 2005). The turbulent flow conditions within the SST are described by the Reynolds-averaged Navier–Stokes equations with a k–ε turbulence closure (Rodi, 1980). For settling, density and rheology features special modules have been implemented. SS transport processes are calculated by the advection-diffusion equation with terms describing settling and thickening based on the settling function. The latter was calibrated by a series of in situ settling tests. The governing equations are numerically solved by the CFD code ANSYS FLUENT 14 by means of an implicit unsteady segregated solver on a boundary-fitted finite volume grid.

The continuity (conservation of fluid volume) equation in its axisymmetric 2D form is written as

$$\frac{\partial rU}{\partial r} = \frac{\partial rV}{\partial r} = 0, \tag{1}$$

Whereas the conservation of momentum in the radial r- and vertical y-directions are

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial r} + V\frac{\partial U}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\nu_t\frac{\partial U}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial y}\left(r\nu_t\frac{\partial U}{\partial y}\right) + S_U, \tag{2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial r} + V\frac{\partial V}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\nu_t\frac{\partial V}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial y}\left(r\nu_t\frac{\partial V}{\partial y}\right) + g\frac{\rho - \rho_r}{\rho} + S_V, \tag{3}$$

where U and V are the time-mean velocity components in the r and y directions, respectively, p is the general pressure less the hydrostatic pressure at reference density ρ_r; ρ is the fluid density, g is the acceleration of gravity, ν_t is the eddy viscosity, S_U and S_V are further stress terms (Krebs, 1991).