Improving wastewater treatment plant performance by applying CFD models for design and operation: selected case studies

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ABSTRACT

Hydrodynamic simulation (CFD: computational fluid dynamics) is one of the major tools for planning the reconstruction and operation of the structures in wastewater treatment plants, and its routine use is commonplace because of the cost savings and efficiency gains that can be achieved. This paper provides examples of how CFD can contribute to substantial improvements in the overall efficiency of wastewater treatment plants.The case studies presented in the paper include rarely investigated issues, such as the operation of aerated grit chambers, performance of primary settling tanks, mixing performance in oxidation ditches and return sludge control. The results show that: (1) air intake rate can be strongly decreased in most of the grit chambers, (2) optimization of the inlet geometry design of primary settling tanks is crucial, especially at high loads caused by storm events, (3) mixer performance design based on current design guidelines is often of an unnecessarily high capacity, (4) sludge recirculation rate should be optimized by CFD investigations based on secondary settling tank performance.

Key words | aeration, grit chambers, mixing, operation, return sludge control, water resources recovery

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HIGHLIGHTS

- Results of little-investigated processes are shown in the paper.
- Air intake rate can be strongly decreased in most of the grit chambers.
- Optimizing primary settling tank performance leads to an enhanced removal efficiency, especially at high load (for example, storm events).
- Grit chambers, primary settling, mixing and return sludge control should always be optimized by computational flow dynamics (CFD) simulations.

INTRODUCTION

Hydrodynamic simulation (computational fluid dynamics: CFD) is one of the major tools for planning the reconstruction and operation of the structures in wastewater treatment plants (WWTPs), and its routine use is essential due to the cost savings and efficiency gains that can be achieved.

To find ways to enhance the efficiency of WWTPs, detailed investigations of all treatment steps require careful analysis.

The illustrated examples presented in this paper show that flow simulation greatly helps to improve the operation and geometry of structures by simple means. Fine-tuning without any investment (operational modifications), or with minor investment, would achieve significant improvements in the efficiency and energy consumption of the facilities (for example: Hunze 2005; Karpinska & Bridgeman 2016; Samstag *et al.* 2016; Wicklein *et al.* 2016; Laurent *et al.* (in press)).

In this paper, results of selected research projects are shown, including recent examples for the role of CFD in supporting the efficiency of WWTPs. The case studies

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highlight issues that are rarely addressed in studies published over the last decade (Figure 1):

– air intake rate in grit removal chambers,
– primary settling tanks with low and high load situations,
– mixing in oxidation ditches,
– return sludge control.

MECHANICAL TREATMENT STEP

Advanced biological treatment concepts require increasingly efficient mechanical treatment, such as screening, grit and grease removal and primary settling. The following studies show two examples of the importance of an optimum air intake in grit removal chambers, and the inlet geometry design of primary settling tanks.

Aerated grit chambers

The task of grit removal chambers is to remove sand and grease from the wastewater as efficiently as possible. At the same time, sludge (with high organic matter content) should not be allowed to settle significantly together with grit, as this results in the loss of valuable organic matter for biological treatment and digester gas production. If the grit removal chamber has excessive separation removal efficiency, a large amount of sludge is also settled with the grit. However, in the case of poor efficiency, a significant amount of grit continues further on to the following units of wastewater treatment technology, causing considerable operational problems (wear, digesters filled with sand, etc.).

Grit removal chambers should be designed as described above to ensure that grit particles with a diameter of between 0.1 and 1 mm will be settled, but that organic matter with smaller particle size and specific gravity (sludges) will pass to the biological treatment stage and sludge digestion, so as to increase biogas production and electrical energy production.

In one of our research projects a 3D CFD model was developed, which is able to calculate the two-phase flow of water and air (Eulerian approach) with the transport of grit of variable particle size distribution at the same time. The CFD model was calibrated and validated against full scale measurements on three full scale aerated grit chambers (Hirschbeck 2010). The validation criteria were:

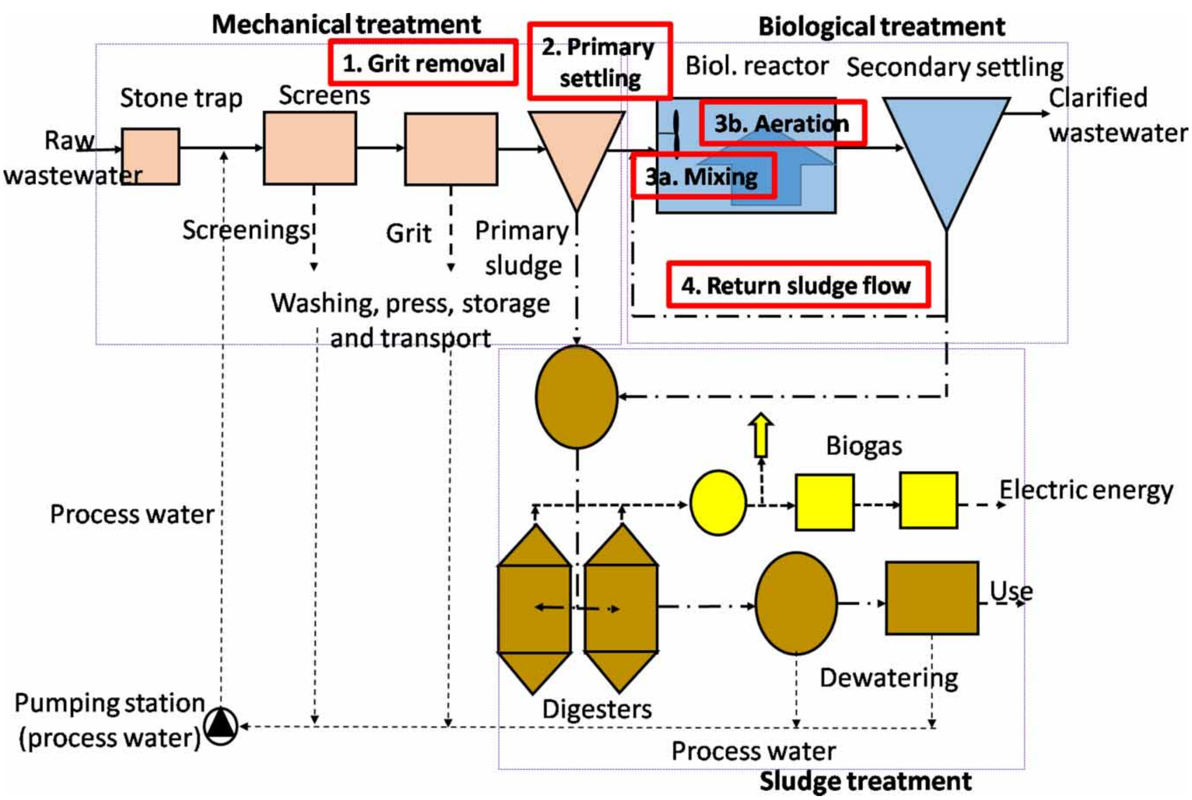

Figure 1 | Flow scheme of a large municipal WWTP illustrating some of the little-addressed processes in wastewater treatment, which have enormous improvement potential: 1. aeration of grit removal chambers, 2. primary settling tanks, 3. counter-action of mixing and aeration in oxidation ditches, 4. return sludge control.

the flow velocities, turbulent kinetic energy, bottom shear stress and removal rate of solids.

The validated model was used to evaluate the grit removal chambers of a WWTP in Hungary, where our target was to optimize the air intake: for example, one with an average daily load of 3,600 m^3/d (Figure 2).

It is known that the air intake induces the typical cylindrical flow in aerated grit chambers, which decisively influences the effectiveness of the grit removal chamber.

The efficiency of aerated grit removal chambers is thus determined by the cross-sectional flow structures. Aeration is therefore a variable operating parameter that directly determines the operation of the grit removal chamber.

The effect of aeration control is illustrated in Figure 3.

This example demonstrates how the aeration rate (0.4, 0.8 and 1.4 $m^3/m^3{\cdot}h$) affects the efficiency of the grit removal chamber. An increasing air flow increases the cylindrical flow velocities. If the cylindrical flow is too slow (i.e. little air is supplied), a large amount of sludge will settle together with the grit. The results are: excessive separation of organic matter (sludge) in the grit removal chamber, grit which is rich in organic matter, and a reduced amount of organic carbon being forwarded to primary sedimentation (digestion) and biological treatment. This affects biogas formation (in large plants) and the efficiency of biological treatment (denitrification bacteria will get less organic carbon source).

On the other hand, in the case of excessive aeration, the efficiency of sand separation decreases, which causes operational problems at the WWTP.

A significantly improved method is to control the air intake rate as a function of the bottom flow velocities (Figure 4).

Figure 4 shows that air intake rates recommended by current design guidelines are causing the flow velocities and turbulences to be too high, which results in low solids removal efficiency and increased energy uptake. In the case of the presented grit removal chamber, low air intake rates are recommended (<0.1 to 0.5 $m^3/m^3{\cdot}h$), which are significantly lower than current design suggestions of

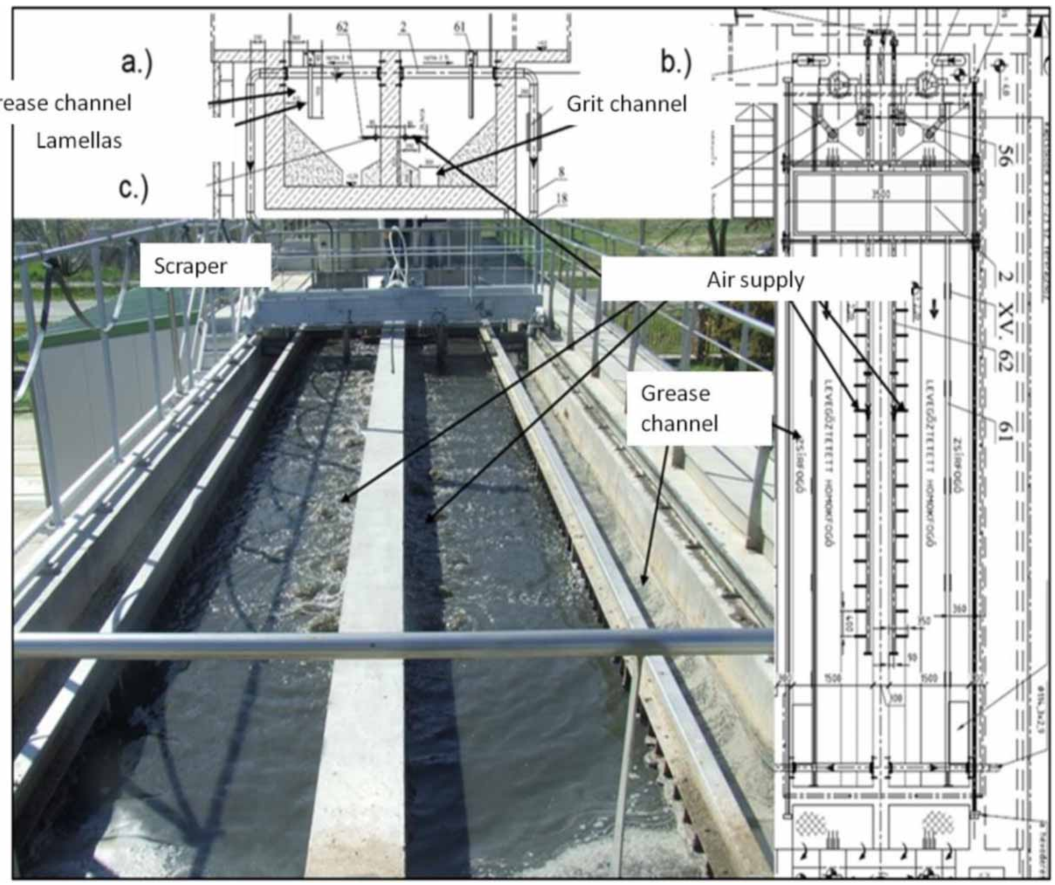

Figure 2 | The investigated aerated grit chamber with an average hydraulic load of 3,600 m^3/d.

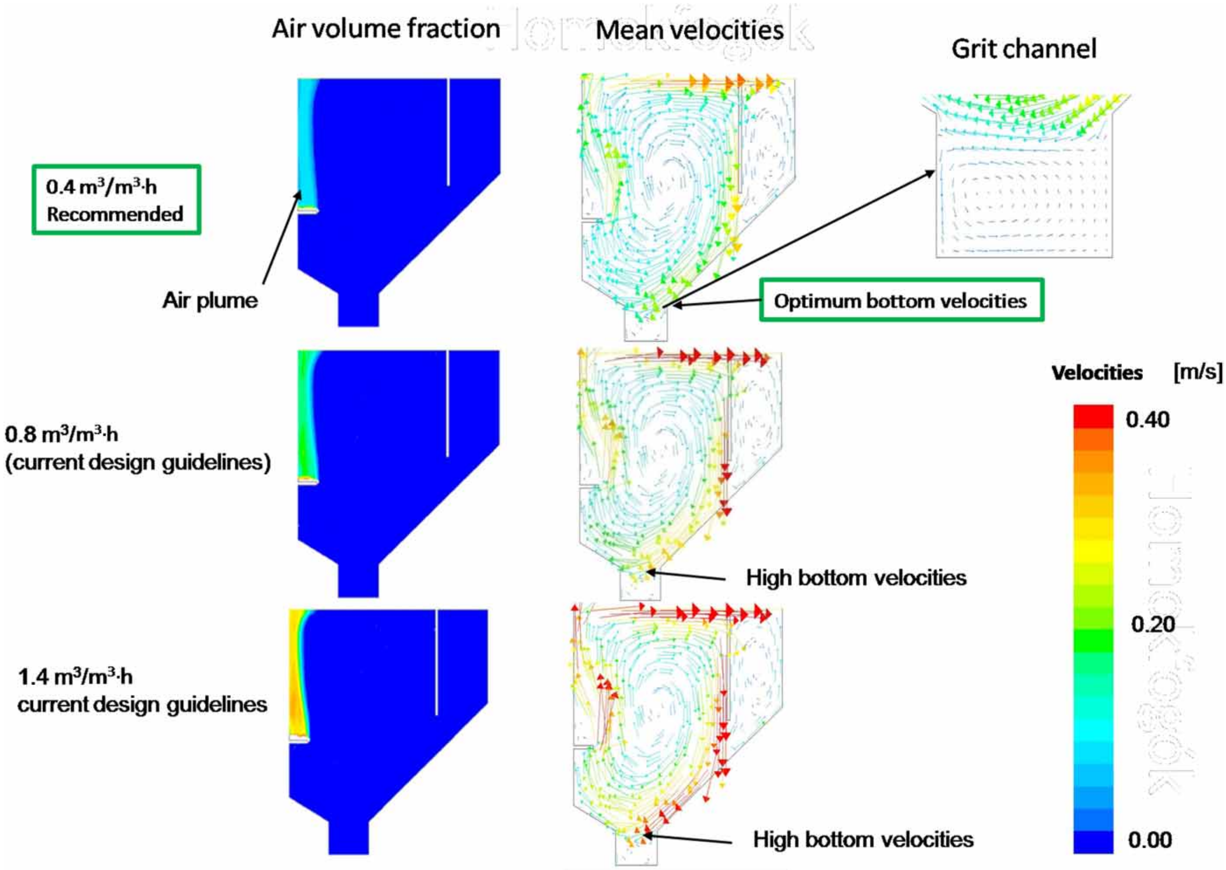

Figure 3 | Air volume rate and flow pattern in the investigated aerated grit chamber at various air intake rates – cross-section.

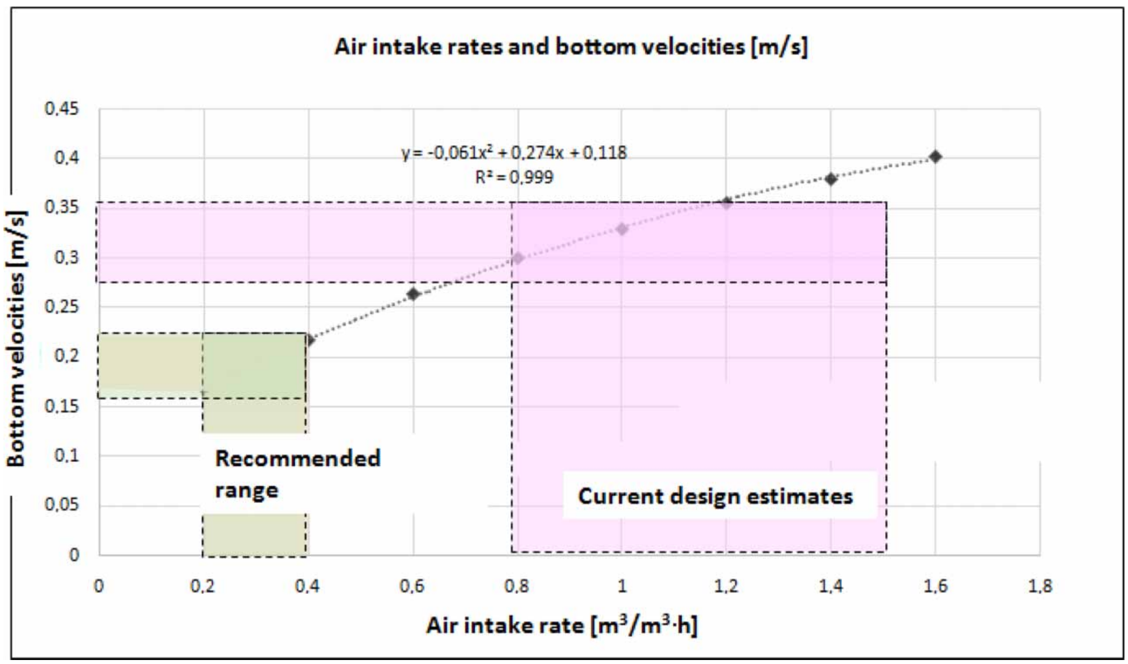

Figure 4 | Bottom flow velocities at different air flows – recommended and current design estimates.

between 0.8 and 1.5 $m^3/m^3 \cdot h$ (Hirschbeck 2010). Consequently, there is no general value for the aeration rate of the grit removal chamber because it depends on the size and the cross-sectional geometry.

The results suggest that the air intake rate can be significantly decreased in most of the grit chamber designs based on the current design guidelines (Figures 4 and 5).

However, the organic content of the grit removed must be continuously monitored in order to avoid the removal of too high an organic content (primary sludge), if the air intake is decreased, even though a velocity range of 0.20 m/s is theoretically large enough to keep primary sludge in motion but low enough to ensure the settling of grit (Figure 5).

Primary settling tanks

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 (Patziger & Kiss 2015).

The removal of particulate organic matter increases gas production in anaerobic digesters, but excessive removal will deprive the biological nutrient removal process of carbon, used for biological nitrogen and phosphorus removal. Efficiently operating PSTs allow the optimum energy generation of a WWTP by removing as much particulate chemical oxygen demand in the PST as possible, without impairing the biological nitrogen removal. Approved design procedures and boundary condition driven control strategies (capacity used, scraper mechanism, sludge removal) need to be developed that will contribute to a satisfactory PST function.

Figure 6 shows the CFD investigation of a circular primary sedimentation tank at a WWTP with a capacity of 64,000 PE.

This is a good example demonstrating that slight differences in the inlet design may lead to considerable differences in efficiency, even in the case of PSTs.

Looking at the differences between a deep inlet position (left) and a high inlet position (right), there is no significant difference in the case of dry weather inflow (76 and 125 l/s), which is the design condition for primary settling tanks. However, in the case of storm water inflow conditions (560 l/s), a significant improvement can be achieved. Lower velocities along the tank bottom lead to a better settling thickening performance and removal efficiency, and thus a more efficient sludge transfer into the digestion step.

The design principles of the inlet structure of PSTs largely differ from those of secondary settling tanks (SSTs), where a rather deep inlet position is preferred. In PSTs, density effects, characteristic of SSTs, such as 'density waterfall' in the inlet zone and density currents within the settling zone, can be ignored.

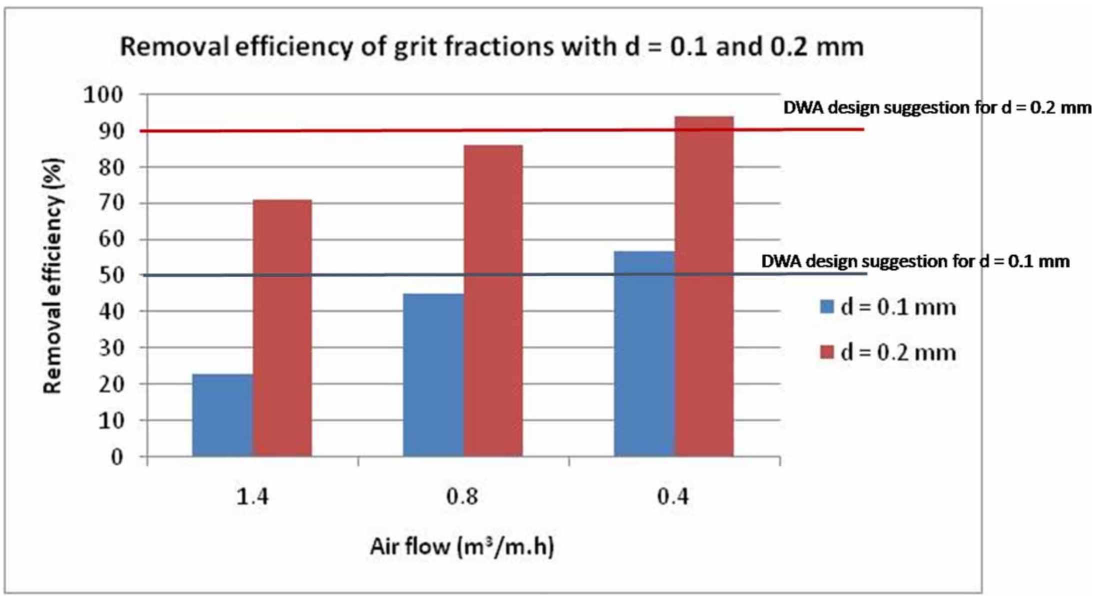

Figure 5 | Removal efficiency of grit fractions at different air flows – recommended and current design estimates.

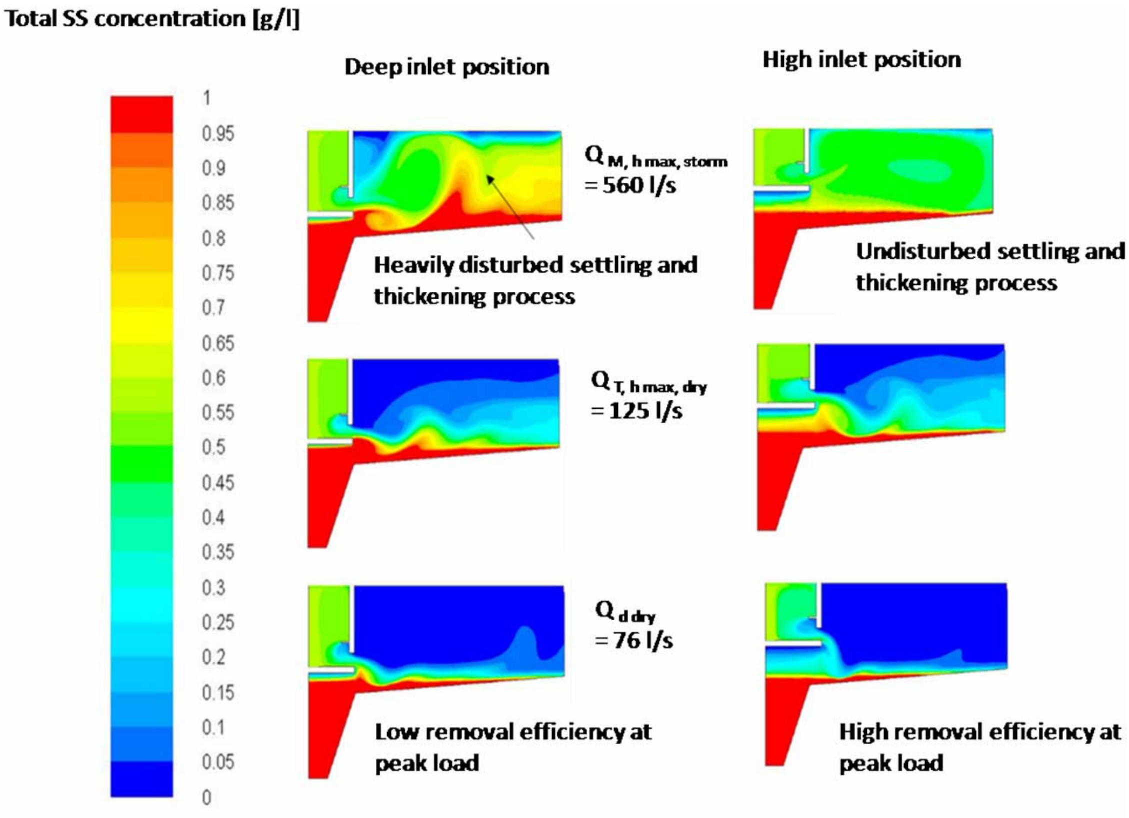

Figure 6 | Concentration patterns in the investigated primary settling tank at various load rates, with a low inlet position (left) and a high inlet position (right). $Q_{M,\ h\ max,\ storm}$: maximum flow rate by storm events (l/s); $Q_{T,\ h\ max,\ dry}$: maximum flow rate by dry weather (l/s).

A reasonably higher PST performance (total suspended solids (TSS) removal >50%, sevenfold increased average TSS concentration within the sludge hopper) can be achieved by shifting the inlet to a high position.

Optimizing performance in primary settling tanks leads to an enhanced removal efficiency, especially at high load (for example, storm events), which in turn leads to a decreased load at the biological treatment stage and an increased biogas and energy production. These results for circular PSTs confirm the measurement and simulation results found in the case of a rectangular PST (Patziger & Kiss 2015; Patziger *et al.* 2016).

BIOLOGICAL TREATMENT STEP

Biological treatment plays a major role in the energy efficiency of WWTPs. Local design and operational features have a crucial influence on the overall conditions of the biological treatment stage and the air intake rate required. In most cases an enormous potential improvement can be detected in the aeration and mixing processes in biological reactors.

Biological reactors

Our investigations were carried out at one of the circular tanks with fine bubble aeration tanks of a WWTP with a capacity of 1.6 million PE, in which simultaneous denitrification and nitrification take place. This is a typical reactor setting for municipal WWTPs of over 1 million PE. The investigated WWTP has an average hydraulic capacity of 300,000 m^3/d and a maximum of 900,000 m^3/d in case of wet weather. The biological treatment takes place in 18 activated sludge lines operated in parallel. Each of them has a length of 61.00 m, a width of 18.20 m and a depth of 8.20 m.

A total of 2,176 air diffusers and six mixers are situated in each reactor. Each mixer has a performance of 5.30 kW. The air intake ranges between 3,000 and 5,000 m^3/h in each reactor, whilst the air blowers have a maximum capacity of 8,000 m^3/h (3.96 m^3/h.diffuser).

The rate of aeration (air intake and aerated time periods) is currently controlled by the continuous on-line monitoring of ammonium and the dissolved oxygen (DO) concentration within the tank.

In the anoxic phases no aeration takes place. Under such operating conditions it is solely the mixing and the geometric features which determine the hydrodynamic processes in the tank. The goal is to keep the activated sludge and water completely mixed for denitrification. It is essential that the mixers maintain bottom-near velocities of 0.15–0.20 m/s in the case of badly settling sludge and low sludge concentrations (sludge volume index (SVI) >140 l/kg, mixed liquor suspended solids (MLSS) = 2–3 kg/m^3), and 0.20–0.25 m/s in the case of good sludge settling characteristics and higher sludge concentrations (SVI <120 l/kg, MLSS = 2–3 kg/m^3). Generation of higher velocities than those recommended above unnecessarily increase the energy uptake of the mixers (W. Frey, http://www.aabfrey.com/, cited by Füreder *et al.* (2018)).

In the research programme, the required thrust of the mixers was investigated in the anoxic as well as in the aerated phases.

An Ansys Fluent based Euler-Euler type of water–air two-phase model was set up for the investigations, which also included a function describing the oxygen transfer between air and water as well as the kinetic of the oxygen dissolution. The model was successfully calibrated and validated, taking all operating conditions into consideration: (1) only the mixers are operated and (2) both the mixers and the aeration are operated at different air intake rates (2,000, 3,000 and 5,000 m^3/h). Subsequently a series of operating scenarios were investigated.

Figure 7 shows the flow pattern in the bottom layer 0.2 m above the bottom in the anoxic phase, when the aeration is not operated. The mixers generate higher flow velocities than those recommended in this layer, to avoid sludge settling and to ensure a homogeneous mixing. This leads to unnecessarily high electrical energy uptake. By decreasing the thrust of the mixers by 50%, the average flow velocities in the investigated layer range between 0.2 and 0.25 m/s, which is exactly the optimum range to keep the sludge homogeneously mixed in the medium of the tank without impairing the energy efficiency of the reactor.

The decreased thrust is not detrimental to the large scale processes in the tank. The number of dead zones with flow velocities below 0.20 m/s increases from 3 to 10% of the total reactor volume, which is acceptable. These dead zones in this case mainly include the most upper layers of the tank and some parts of the curves along the guide walls (Figure 8).

Figure 9 shows a strongly heterogeneous DO concentration pattern typical to this type of reactor, resulting in a decreased overall performance of the tank with respect to the treatment and energy efficiency.

The results show that the mixing performance has little influence on the DO concentration pattern.

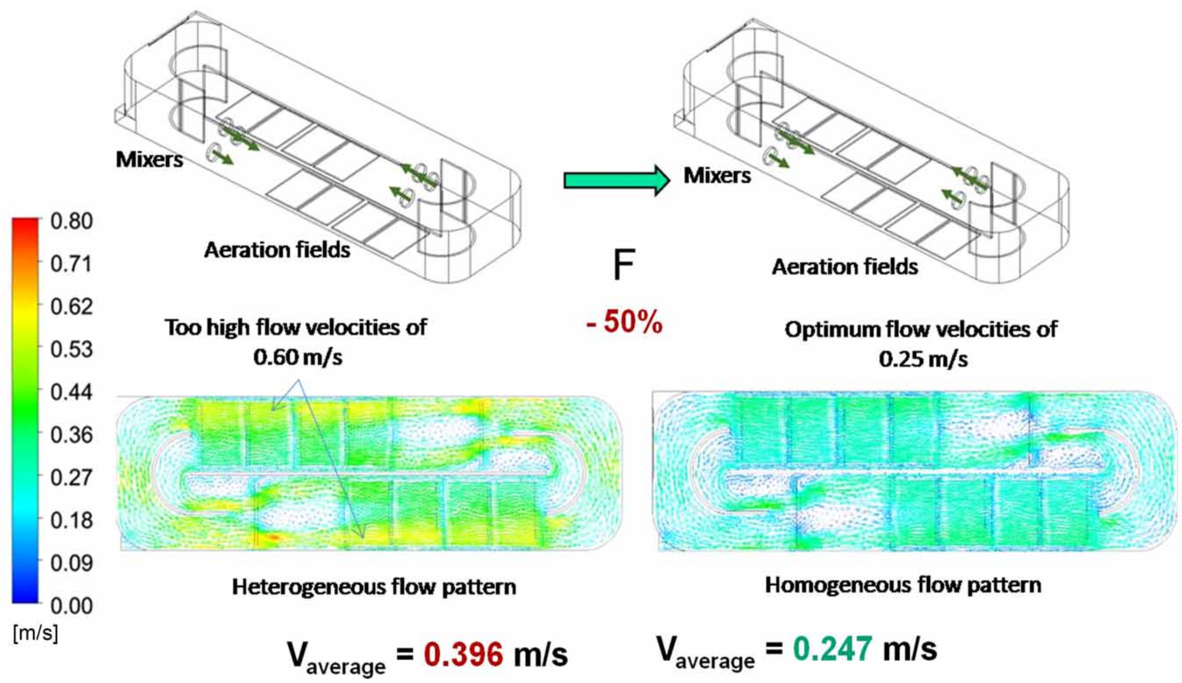

Figure 7 | Flow pattern in the bottom layer 0.2 m above the bottom in the anoxic phase (mixing on, aeration off). F: thrust (N); $V_{average}$: average flow velocity (m/s).

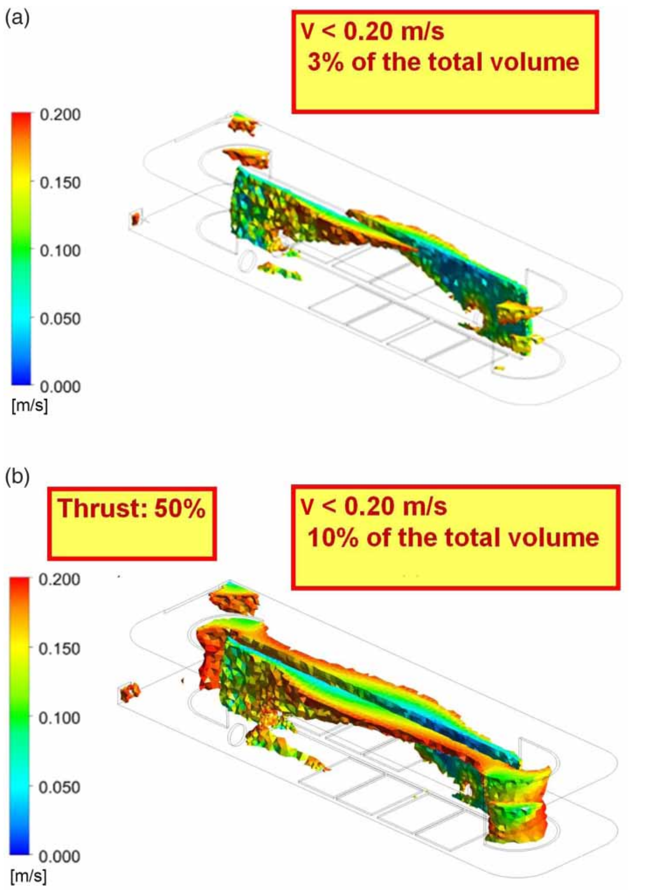

Figure 8 | Regions of the aeration tank, where the flow velocities (V) are less than 0.2 m/s (dead zones) in the anoxic phase (mixing on, aeration off): (a) thrust at 100%, (b) thrust at 50%.

Even a powerful increase of the thrust up to 150% (5,700 N) does not achieve a significantly better homogenized DO pattern, which would be a key to a more efficient operation in the aerated phases. Neither does a decrease to 50% affect the DO concentration distribution to any significant degree.

Consequently, a large decrease in the thrust of the mixers (50% on average in the case of the investigated tank) leads to considerable energy savings without compromising the aeration, and thus the wastewater treatment efficiency.

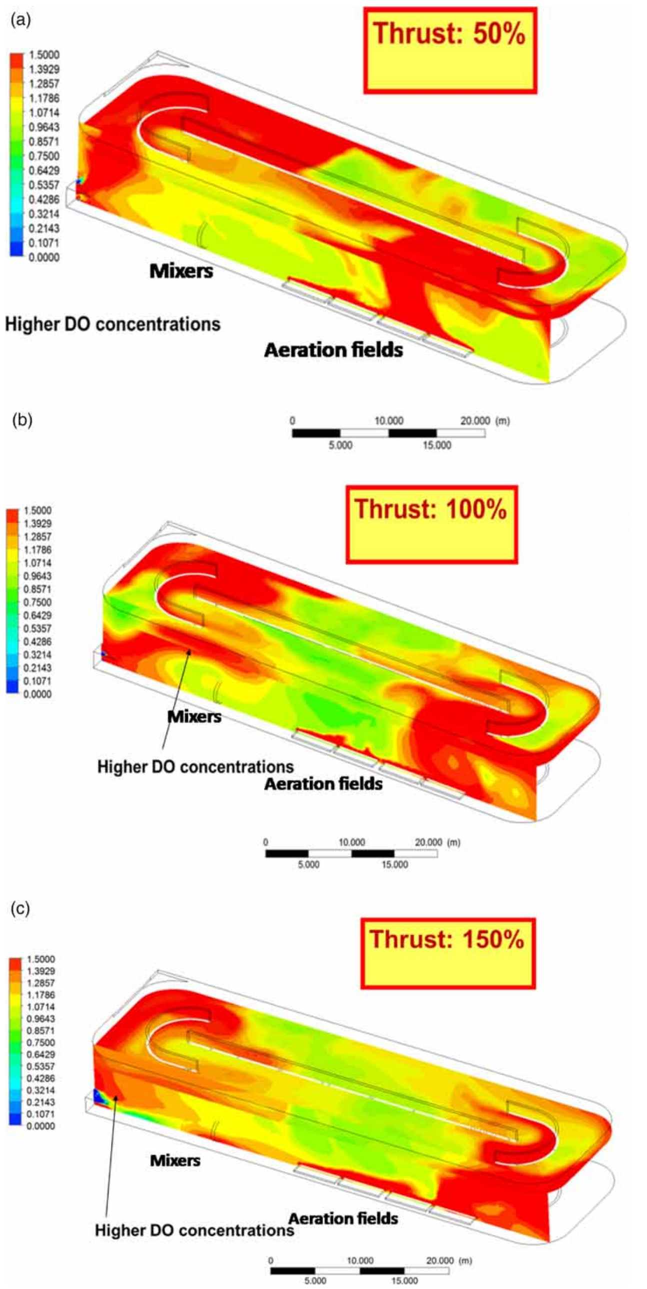

Figure 9 | There is no significant influence of the mixer's performance on the dissolved oxygen concentration distribution to be observed with a thrust of (a) 50%, (b) 100% or (c) 150%.

Return sludge control

CFD is an essential tool used to optimize the return sludge control.

In a research project (Patziger *et al.* 2012), we investigated the optimal return sludge flow required to maintain an overall optimum efficiency, by minimising the sludge mass stored in the SST and maximising the sludge mass in the biological reactor at the same time. A key point here was to keep the return sludge concentration as high as possible at a given return sludge flow. Low return sludge flows lead to insufficient sludge transport from the SSTs into the biological reactors, while high return sludge flows lead to overload (increased surface load) of the SSTs.

To investigate the mass balance in activated sludge systems, including the fine scale processes, a mass balance model was developed comprising an axisymmetric 2D SST model and a mixed reactor relating to the aeration tank. This provided a detailed insight into the complex flow and transport processes in the SST during the investigated time period. The model calibration and verification process was carried out for a circular SST (D = 50 m), part of the WWTP at Graz which was representative of a medium size European city, with a capacity of around 500,000 PE. This provided ideal conditions for detailed analysis, offering at the same time the opportunity of reasonable generalization in its category.

As a result of the project we found that there are two key factors influencing the return sludge concentration: the optimum inlet height and the optimum rate of return sludge flow.

Due to the higher density of the inflowing liquid (water–sludge suspension) compared to the medium density in the SST, a quite high inlet position (high potential energy) leads to large downward velocity components. This results in the high kinetic energy of the inflowing jet and the density current. Large turbulent regions, distinct turbulent structures and a wavy sludge–water interface lead to a deteriorating flow pattern, settling and thickening (Krebs 1991).

The better flow pattern observed directly at the inlet is characterized by lower potential and kinetic energy, and improves the layering of the entering jet. This results in better settling and thickening conditions and consequently a denser sludge layer (Figure 10), a higher returned sludge concentration and a decreased sludge mass in the SST. All these effects lead to a higher SST performance.

With respect to the optimum range of return sludge flow, we found that a low return sludge flow rate when applied with a return sludge ratio of less than 0.5 leads to high maximum sludge mass in the SST. However, in a highly consolidated form (Figures 11 and 12(a)) there is insufficient sludge return for sludge transport. In a range of a return sludge ratio of between 0.5 and 0.7 the transferred sludge mass could be reasonably reduced (Figures 11 and 12(b)). By applying a high return sludge flow rate with a return sludge ratio of more than 0.7, the increased SST load disturbs the settling and thickening processes (excessive return sludge flow, Figures 11 and 12(c)). In this upper range of the return sludge flow rate the transferred sludge mass increases, and consequently the maximum sludge mass also increases in the SST. Further details of this return sludge control strategy, the model validation and model quality are described in Patziger *et al.* (2012). When optimizing return sludge ratio, care has to be taken of the

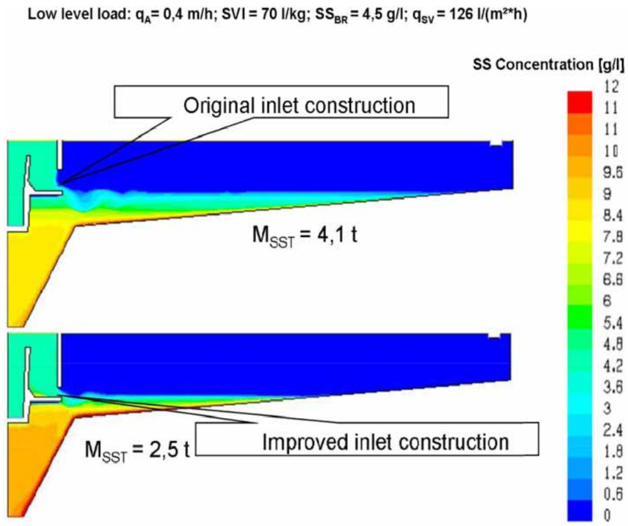

Figure 10 | Influence of the inlet height on the return sludge concentration. q_A: surface overflow rate (m/h); SS_{BR}: suspended solids concentration in the biological reactor entering the SST (g/l); q_{SV}: sludge volume overflow rate (m/h); M_{SST}: sludge mass in the SST (t).

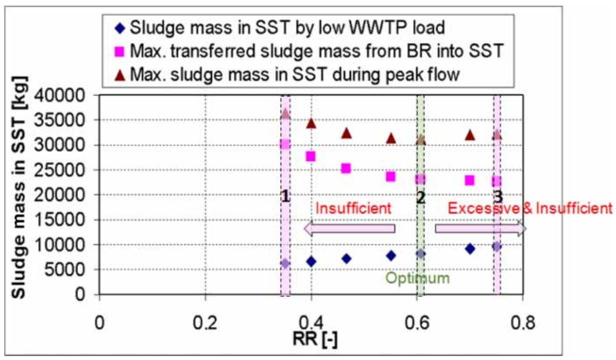

Figure 11 | Sludge mass in the investigated SST at different return sludge flow rates. RR: return sludge flow ratio; BR: biological reactor.

nitrogen and phosphorus removal efficiency too. This example shows the hydraulic limits determined by the SST performance.

CONCLUSIONS

Rarely investigated processes such as grit chambers, primary settling, mixing and return sludge control should be optimized as a very significant element of large WWTPs.

Grit chambers designed and based on current guidelines are over-aerated. CFD simulations suggest that air intake rates from 0.1 to 0.5 $m^3/m^3 \cdot h$ would ensure optimum flow behaviour for grit separation, which is significantly lower

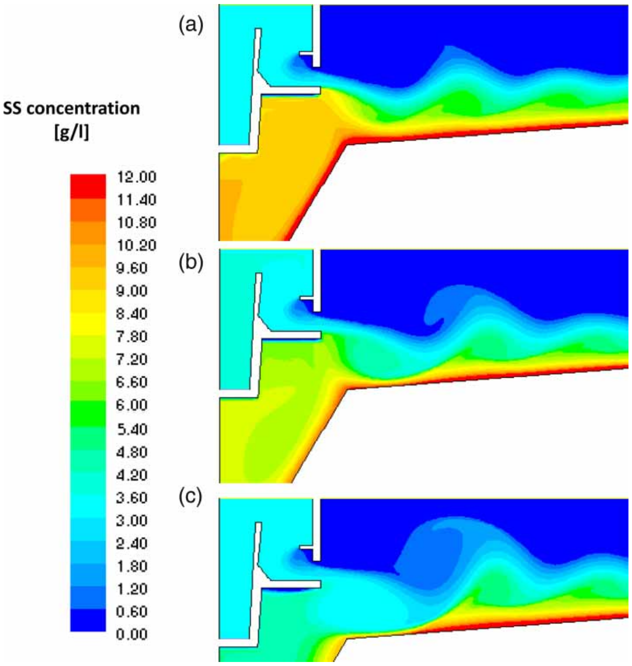

Figure 12 | Concentration pattern peak load in the investigated SST at (a) a low (0.38) (b) an optimum (0.6) and (a) high (1.0) return sludge flow rate.

than current design suggestions of between 0.8 and 1.5 $m^3/m^3 \cdot h$. Air intake rate can be significantly decreased in most of the grit chambers.

Optimising primary settling tank processes leads to an enhanced removal efficiency, especially at high load (for example, storm events), which in turn leads to a decreased load at the biological treatment stage and an increased biogas and energy production.

Mixer performance is often of an unnecessarily high capacity. As the example of an oxidation ditch frequently applied to biological treatment indicated, optimizing the mixer performance would result in remarkable energy savings.

Sludge recirculation rate should be optimized by CFD investigations. Generally, a range for sludge recirculation rate (Q/Q_R, where Q is inflowing flow rate, l/s; Q_R is return sludge flow rate, l/s) from 0.5 to 0.7 proved to be the optimum range.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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