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Operation improvement of sequencing FED-batch wastewater treatment

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ABSTRACT

Sequencing batch reactor systems in wastewater treatment is widely applied activated sludge technology. The system performance is not only dependent on the raw sewage quality and biochemical processes, but the flow pattern within the reactor has a significant impact on the treatment itself. The varying stages of the operation require different fluid flow conditions; biological stage shall be appropriately mixed, whereas low velocity zones favor the phase separation. The aim of this study was to improve sequencing batch reactor operation in order to optimize the treatment efficiency. Numerical fluid dynamic simulations were performed to determine the substrate and biomass homogeneity inside the reactor at the biological phase and the rate of the decantation was estimated at the sedimentation phase. The settling model was calibrated by field measurements. The results revealed that the hydraulic efficiency of the reactor was 87% and the achievable settled solid content was 0.9%.

KEYWORDS

batch reactor, fluid dynamics, mixing efficiency, sedimentation, wastewater treatment

1. INTRODUCTION

Sequencing Batch Reactor (SBR) gained popularity in wastewater treatment since it is a single tank design, flexible system, with relatively easy automation [1]. The system configuration is quite simple; the tank has an inlet and outlet structure, mechanical mixers and diffusers. The flow within the tank can be plug flow or completely stirred. The treatment stages are separated by time. One cycle includes filling, mixing without aeration, mixing with aeration, sedimentation, decantation stages. As a start of a cycle the primary treated sewage is introduced to the system. In municipal wastewater treatment the plant influent is continuous but unevenly distributed following a diurnal pattern. Prior the batch reactor an equalization tank may be required depending on the actual flow variation and the number of the parallel applied SBRs. In large capacity plants, where more than three tanks are in operation, the incoming flow may be filled to one of the units at all time and then equalization tank is not required. Biological stage is designated to remove organic matter and nutrients from the wastewater. Based on the presence of oxygen three conditions can be distinguished; anaerobic, anoxic and aerobic. Aerobic microorganisms are responsible for organic component degradation and nitrification, anoxic condition is required for denitrification, whereas anaerobic-aerobic varying environment facilitate the phosphorous accumulating biomass growth [2].

Presence of Dissolved Oxygen (DO) in water phase is created by diffusers, but when the aeration is turned off, anoxic and anaerobic conditions develop due to the oxygen consumption of the biomass. Mixing is a key element in the process, since it provides the mass transport between the microorganisms and bulk flow. Mixing can be induced by the aeration, mechanical mixers or introducing fluid discharge through an inlet structure. As a consequence, different processes provide the mixing at the various stages. During filling, the discharged flow, during anaerobic and anoxic stages the mechanical mixers, whereas the

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aerobic stage utilizes both the mechanical mixers and the aeration power. At sedimentation and decantation no mixing mechanism is provided.

The structure of the biomass can be suspended (activated sludge), attached to a carrier (biofilm) or granulated. Activated sludge technology applies suspended biomass, it contains the microorganisms. Biofilm reactor can be operated as batch system. The attached biomass is submerged and the biofilm shall not dry out during the process, therefore the decantation volume in one cycle shall be less than 30% of the total volume. Removal efficiencies of organic matter in biofilm SBRs are reported to be more enhanced compared to traditional SBRs, but depending on the media it can show some disadvantages [3]. Aerobic granular sludge technology in batch operation is able to combine the high organic removal efficiency and flexible operation. Industrial wastewater rich in carbon source can be treated effectively [4–5].

In sedimentation phase there is no aeration and mixing. During phase separation the sludge blanket level is decreasing, below the blanket the dry matter concentrates. The supernatant – the treated water – is decanted at the end of the cycle and the thickened sludge is removed.

It can be seen from the above process description that optimization of cycle and phase times have effect on the system performance. There is evidence that the load could have been increased and energy saved by the optimization of SBR cycles [6–7]. Even the on/off control of DO can be further improved by adding air flow meter to the reactor and applying fuzzy logic [8]. However, model based optimization may lead errors, the model domain may not cover all aspects of the system, primarily the settling and microbial community adaptation [9].

Mass balance based models describe the fate of the scalar variable within the reactor, predict the effluent quality in function with the input data (e.g., raw sewage characteristics, dissolved oxygen concentration, biomass amount). It has a long tradition to use Activated Sludge Models (ASM) model family [10], therefore a lot of experience is gained in model calibration and validation procedure. These models focus on biokinetic aspects of wastewater treatment and an effective tool in process sizing and in operation optimization [11]. Hydrodynamics in these models are simplified, in spite of the fact that a treatment deficiency may be derived from a hydraulic failure [12]. To reveal the fluid flow behavior within the tank Computational Fluid Dynamics (CFD) is an option, which can be coupled ASM [13]. CFD-ASM coupling have advantage in reactor model development, but computational cost related to the level of complexity, which can be handled limits its applicability [14]. Good modeling practices for CFD approach of wastewater treatment is presented in the literature [15] with an extensive state of the art overview [16]. Many applications have been developed applying robust numerical modeling, but it has still limitations. The fixed density modeling in wastewater treatment is a common practice in design, but it may over predict the degree of mixing. It is unaddressed to model coupled aeration tank and clarifier system to predict inter connected flow and mass transport in unsteady flow conditions [17].

Deterministic models are widespread in wastewater treatment, but stochastic tools in water quality modeling can be popular in water management [18].

Purpose of this study is to optimize the mixing during the biological stage and determine sludge management via the predicted settled solid concentration at the end of the phase separation stage in an SBR system.

2. METHODOLOGY

Nowadays, CFD can be considered as a modern, accepted method in the design of wastewater treatment technologies, in the control of various operating conditions and in technological developments. The spatial and temporal distributions of the field variables determining the hydrodynamics are calculated based on the numerical solution of the governing equations. The method of finite volumes is widespread in fluid science, which divides the flow domain into elementary volumes and thus solves the basic conservation equations of mass and momentum. CFD is able to map fine flow structures and describe multiphase flows.

Reynolds averaging of equations in space and time is the most efficient way to solve the equations, but it must be supplemented by other models describing turbulence. In this study InterMixingFOAM solver was used to solve multiphase flow, where the main phase was water and the side phase was the sludge.

Semi-implicit method for pressure-linked equations algorithm was used. It is an iterative procedure for solving equations for velocity and pressure. Linear upwind differencing interpolation scheme was set for numerical solution.

Sludge settling characteristics were measured via field measurement. It was performed with the help of a measuring cylinder with a plastic base, the height of which is 415 mm, and its division is notched every 10 mL. Samples were taken from the operating batch reactor during the aeration cycle. The sample was poured into the measuring cylinder and the sedimentation was examined for 1 h. During the settling time, sludge volume values were recorded every 5 min in order to determine a settling curve.

Linear part of a batch settling curve corresponds to the hindered settling and the phase separation velocity can be determined from the slope of the linear part. Parameters derived from a dilution experiment are able to describe batch settling curves provided the rate of descent of the sludge blanket is moderate. Vesilind type of sedimentation fails if there is a rapid sludge blanket movement [19]. The reason for the discrepancy is the compression zone processes. At flocculent settling the particles could aggregate and no free flow conditions are met. The flocculent settling coefficient used as a model calibration parameter, but the threshold of flocculation method proved to be an efficient tool to determine this parameter mechanistic. It describes the minimum solids concentration needed to get a significant formation of flocs settling and one of the most significant advantages of this approach is that it can easily and routinely be measured by plant operators [20].

Numerical model shall reflect to this velocity via the effective particle diameter (Stokes equivalent diameter), therefore the model calibration procedure was on trial and error basis, an adjustment of the particle diameter to get the same result as in the field experiment.

Thickened sludge concentration is an important parameter in sewage treatment plant operation since it determines the sludge line performance directly. Settling can be enhanced by adding external material [21], but in most of the cases the suspended matter aggregates and thickens. Sludge settling shall be facilitated at settling stage, and it should be avoided at the biological stage, therefore two modeling alternatives were investigated. Initial condition of the first model setup was a homogenized two-phase system and the sludge blanket height and thickened sludge concentration were estimated in function with time.

The second model run was steady-state with one mechanical mixer in operation. This setup corresponds to anoxic condition and the sludge homogenization and hydraulic efficiency of the reactor were investigated. The reactor shape was rectangular with a dimension of 6 m depth, 13 m of width and 21 m of length in each simulation. The activated sludge material properties were set to constant values (viscosity: 0.01 kg/(m•s), density: 1,050 kg/m^3) based on literature [22].

3. RESULTS AND DISCUSSION

Settleability test was performed in laboratory scale; the procedure was outlined in Section 2. The sludge blanket level decrease was plotted in function with time. The results are shown in Fig. 1. The settling curve presents the four separate stages of settling. The first few seconds is the initial phase, where the particles are positioning, which is followed by the free and hindered settling (1–30 min). After half an hour starts the transition phase (approx. 30–45 min) and at high solid concentration the compression phase (45 min <). One hour later from the measurement start there is no visible changes in sludge concentration. This test was performed three times, but only at one initial solid concentration, there was no dilution necessary. The results from the three tests were similar; therefore it can be used for model calibration. Calibration method was detailed in the previous section; the equivalent diameter was determined iteratively in the CFD simulations.

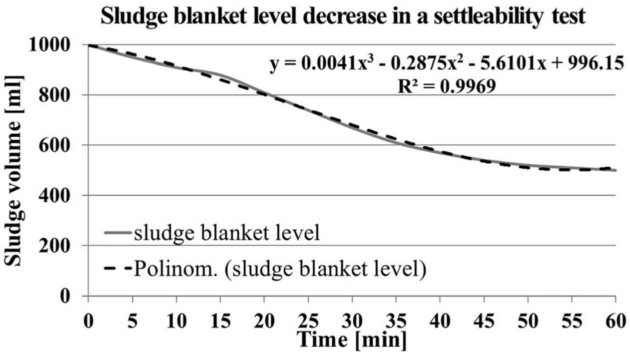

Fig. 1. Sludge blanket level decrease in a settle-ability test

Unsteady simulations were performed with a time step of 1 second assuming 4.5 g/L initial homogenized solid matter concentration. Sedimentation time was 1 h and the concentration increase was observed at the bottom of the reactor as the time advances. The best fit with the field experiment was detected when particle size of 0.2 mm was set.

This calibrated effective diameter is in the range of previous reports [23]. Sludge thickening can be seen in Fig. 2, where the sludge concentration was plotted in function of time. It can be stated that the initial solid concentration doubled at the end of the process. The value of 9,000 mg/L can be converted to dry sold content of 0.9%, which reflects to a good settling process.

During the settling stage multilayered concentration profile developed, at the top of the tank the supernatant dry solid concentration was below the effluent limit of 35 mg/L. This decantation layer had a height of 1.5 m (at 4.5 m height) measured from the bottom of the tank. The sludge blanket level, which visually separate the lower part of the supernatant and the sludge, was at 3.5 m from the bottom. Investigation of the concentration change inside the sludge was not scope of the study, excess sludge removal took place near the bottom region.

Steady-state model run was performed in order to check whether the submersible mixer with 4.65 kW power was enough to keep the biomass in floating. The mixer was installed at 5 m depth as it is noted in Fig. 3 with a black circle. Figure 3 shows the spatial distribution of sludge concentrations, the mixer is marked by a black circle. The simulation assumes a constant biomass amount in the reactor, and the biokinetic processes were not covered in this study.

Two phenomena can be observed; one is the deviation of the solid concentration due to the assymetric mixing concentration, the other one is the amount of particles, which tends to settle out. The sludge concentration near the mixer is less than in the other part of the reactor due to the high

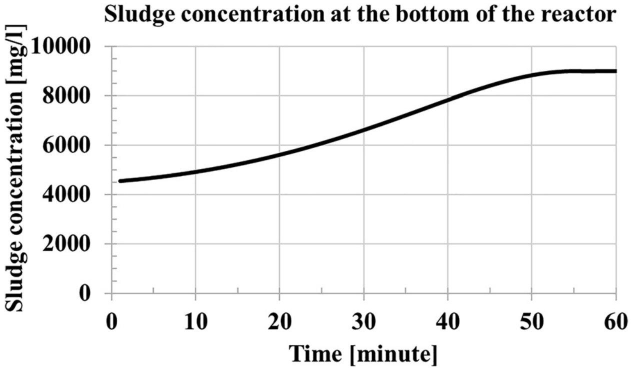

Fig. 2. Sludge concentration increase at the bottom of the reactor during settling phase

movement of the fluid flow. The desired average solid concentration of 4.5 mg/L is achieved at the middle of the tank.

Particle density is above the average at the opposite wall of the mixer. The reason of the accumulation is the horizontal movement of flow, which transport the particles to the opposite side of the reactor, where the wall functions as a boundary. From process point of view, the acceptable range of the biomass concentration is 4–6 g/L and most of the operating volume falls within this range (see Fig. 4).

Biomass concentration above 6 g/L in activated sludge system does not favor settling, whereas the low concentration (<4 mg/L) is not an effective use of the tank volume.

Analyzing the flow velocity magnitudes (Fig. 5) it can be seen that 87% of the total volume has an optimal movement since the velocities in these zones are between 5 and 20 cm/s. In low flow zones (<5 cm/s) dead-zones may develop and high flow zones decrease the hydraulic residence time causing insufficient biological activity. Thus the overall hydraulic performance of the reactor is 87%, which is considered to be appropriate.

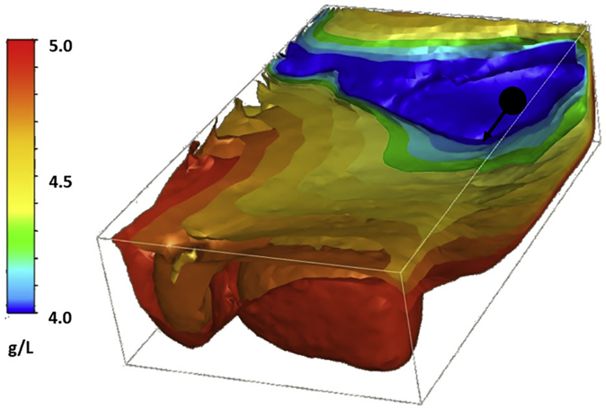

Fig. 3. Sludge concentration contours during biological stage

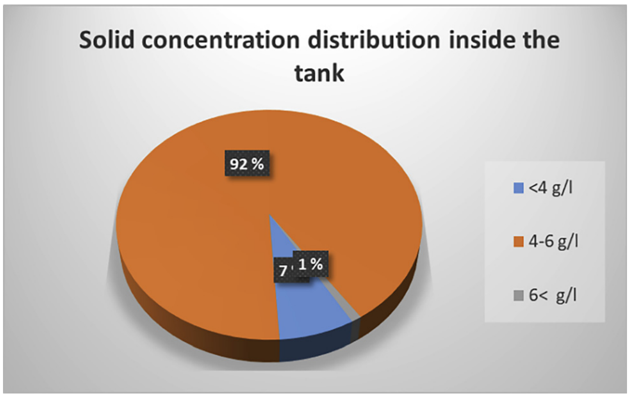

Fig. 4. Solid concentration distribution inside the tank

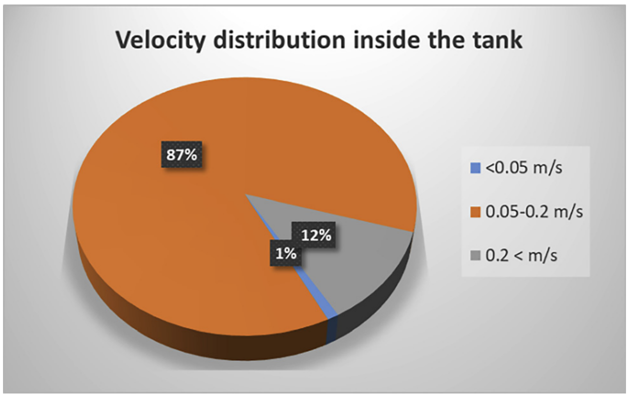

Fig. 5. Velocity distribution inside the tank

The submersible mixer kept the biomass floating even without aeration, and unwanted sedimentation was not detected, therefore the installed power was acceptable. Both model calculations shows a good agreement with field data and satisfy the purpose of this investigation, but it has some limitations and opportunity for further improvements as follows:

- Average effective particle diameter was assumed for solid particles; however the size distribution could be taken into account applying Population Balance Model PBM, which is a sub-model, which can be integrated to the CFD approach. PBM is capable of the following investigations: particle breakage and collision, aggregation, flocculation, de-flocculation [24];
- Non-Newtonian behavior of the sludge was not taken into account. In this study sludge is a fluid, for which the governing equations of fluid flow can be described. Newtonian approach of sludge is valid only until its dry content does not exceed 2–3%;
- Pressure jump was prescribed for the submersible mixer instead of a deforming mesh. Pressure difference between the two sides of the mixer has correlation of the volumetric flow through the mixer. If the mixing power is the available input data, the pressure difference can be determined trial and error basis since the flow is an output data of the simulation. More detailed mixer models resolve the simulation domain more accurately, and the numerical grid would change in time as the mixer is rotating. It would cost a lot of computational resource, but the actual movement of the mechanical device is represented.

4. CONCLUSION

Batch wastewater treatment applications proved its efficiency in the last few decades. System is used at all scales. Large capacity municipal wastewater treatment utilizes robustness of such systems, whereas the pre-treatment of industrial wastewater takes advantage of the easy operation.

There are examples for decentralized wastewater treatment solutions, since the maintenance of the single unit is much easier compared to multi-tank systems.

In this study two critical stages of the processes were highlighted, one is biological stage without aeration, where a single submersible mixer should keep the biomass in suspended form, the other is the sedimentation phase, which goal was to thicken the sludge effectively. In this investigation CFD tools were applied to predict the flow field within the tank. CFD analysis required to build a mesh and set the initial and boundary conditions of the governing fluid flow equations. Multiphase simulation approach had a calibration demand on the sludge particle characteristics; the effective particle size was calculated based on the settling curve of the sludge performed in field measurements at laboratory scale.

As a result, the sludge blanket height and concentration profile was determined, which serves data for operation; the decantation height shall go not under 4.5 m measured from the bottom of the tank and the achievable dry solid content was 0.9%. During the biological stage the nearly 90% of the volume operates as designed, no significant short-circuit or dead-zones are expected, and the biomass would not settle out. This study revealed the direct usage of the model results in practice, however further improvements of the model approaches and deeper understanding of the ongoing processes are necessary for answering more detailed problems.

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