Numerical simulation of secondary sedimentation tank based on population balance model

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Abstract. A technical method of grid flocculation wells is proposed to control the effects of heterogeneous flow on the flow regime and the removal efficiency of suspended solids in the secondary sedimentation tank. The flocculation and sedimentation of activated sludge in sedimentation tanks were simulated by a combination of population balance model (PBM) and computational fluid dynamics. Compared with the prototype of the flocculation well, the grid split the vortex under inertia and the turbulence of the grid, which increased water viscosity, improved the energy dissipation of the flocculation well by more than 40%. The energy consumed by the viscous action provided the power for flocculation of the activated sludge, and reduced the volume fraction of particles with a particle size of less than 98 μm by over 50%. After the addition of No. 2.5 (grid interval is 25 mm) and No. 3.5 (grid interval is 35 mm) grids, the concentration of effluent suspended solids was reduced by 29.3% and 69.4% respectively, compared with the prototype. The average suspended solids concentration of the No. 3.5 model of the actual optimization was 9.2 mg L⁻¹, which was similar to the simulation results, indicating the effectiveness of the optimization method.

1. Introduction
In traditional sewage biological treatment systems, secondary sedimentation tanks are usually located behind biological treatment process as an indispensable part. Its main function is slurry separation and sludge thickening to ensure that the concentration of suspended solids in the effluent meets emission requirements [1]. The hydraulic characteristic in the secondary sedimentation tank has an effect on the flocculation of activated sludge and the breaking of flocs, as well as the sedimentation and secondary suspension of the sludge [2]. Therefore, in the actual working process of the secondary sedimentation tank, the state and structure of the fluid in the pool directly affect the working efficiency of the secondary sedimentation tank [3]. The fluid density of influent is higher than that of the fluid in the secondary sedimentation tank since it contains a large amount of activated sludge. The influent flows to the bottom of the sedimentation tank at a high speed under gravity, forming an underflow and causing surface reverse flow, which makes the actual operation deviate from the ideal sedimentation tank hypothesis [4,5]. Alonso et al. found that central flocculation wells promoted the accumulation of un-flocculated particles while the greater benefit was the improvement in fluid dynamics [6].

Population Balance Model (PBM) is a general method for describing the size distribution of dispersed phases in multiphase flow systems. It is commonly used in numerical simulation of crystallization systems, polymerization systems and particle preparation systems [7]. Biggs and Lant [8] used the PBM to simulate the flocculation process of activated sludge. The simulation results well
predicted the change of floc particle size distribution over time during the flocculation of activated sludge. Ding et al. [9] used experimental data to compare the simulation results of 16 models of aggregation and fragmentation in PBM, and introduced the concept of collision efficiency, which improved the matching between simulation results and experimental results. Li [10] developed and selected appropriate polymerization and fragmentation kinetic expressions within the population balance framework, and only two parameters was needed to estimate: collision efficiency coefficient and damage frequency coefficient. The simulation results indicated that PBM was suitable for describing the flocculation kinetics of activated sludge.

In this paper, PBM was used to simulate the flocculation process of activated sludge in the flocculation well as well as the internal flow state and effluent suspended solids characteristics of the secondary sedimentation tank. The influence of different types of grid flocculation wells on the flocculation process of activated sludge will be analyzed, which could provide the theoretical basis for the selection of grid flocculation wells.

2. Materials and Methods

2.1 Population balance model (PBM)

Parker et al. [11] found that floc polymerization and fragmentation occur simultaneously, which affect the particle size distribution during the flocculation process of activated sludge, and this process is described quantitatively by PBM. Population Balance Equation (PBE) of variation in the number density of particles with volume $v$ could be expressed as follow:

$$\frac{dn(v)}{dt} = \frac{1}{2} \int_{0}^{v} \beta(v-u,u)n(v-u)n(u)du - n(v)\int_{0}^{v} \beta(v,u)n(u)du + \int_{v}^{\infty} b(v|w)S(w)n(w)dv - S(v)n(v)$$ (1)

Where $\beta(v,u)$ is the collision frequency of particles with volume $u$ and $v$, $n(v)$ and $n(u)$ are the number density of particles with volume $v$ and $u$ respectively, $b(v|w)$ is the probability density function of a particle with volume $w$ broken into particles of volume $v$, $S(v)$ and $S(w)$ are the selectivity of particles with volume $v$ and $w$ respectively, $n(w)$ is the number density of particles with volume $w$.

Collision frequency of particles can be defined as follow [12]:

$$\beta(v,u,t) = \alpha(v,u) \beta_0(t) \beta^*(v,u)$$ (2)

Where $\beta_0(t)$ is the polymerization rate constant and $\beta^*(v,u)$ is the correlation coefficient between the aggregated particle size and $\beta(v,u,t)$, $\alpha(v,u)$ is the collision rate of particles of volume $u$ and $v$. The key to the flocculation process is Brownian motion, fluid motion (shearing), and collision between particles caused by sedimentation [13]. In the secondary sedimentation tank, the shearing action usually caused by fluid motion is the main cause of the collision. According to the Smoluchowske shear force equation of Correlation equation between particle size and $\beta(v,u,t)$, Equation (2) can be rewritten as follow [14,15,16]:

$$\beta(v,u,t) = \alpha(v,u) \beta_0(t)(u^{1/3} + v^{1/3})^3 = 0.31G((u^{1/3} + v^{1/3})^3$$ (3)

The fracture kinetics contains two equations: The selectivity equation (Equation (4)) describes the selectivity of particle fragmentation and the fracture equation (Equation (5)) describes the particle size after particle breakage.

$$S(v,t) = S_0(t)S^*(v)$$ (4)

$$\int_{0}^{w} b(v|w)dv = 1$$ (5)

Where $S_0(t)$ is the selectivity constant, and $S^*(v)$ is the selection rate and is a function of particle size [17]:

$$S^*(v) = Av^a$$ (6)
Where \( a = 1/3 \), \( A \) represents breaking rate coefficient as a function of the velocity gradient \( G \). In Eq. 7, \( A' = 0.62 \) and \( \gamma = 0.45 \) [14]. These two parameters are related to flocs strength and structure, respectively.

In order to embed PBM in the calculation program, PBE needs to be discretized. Discretized Population Balance Equation (DPBE) is [18,19]:

\[
\frac{dN_i}{dt} = \sum_{j=1}^{i-2} 2^{j+i-1} \beta_{i-j,j}N_{i-j}N_j + \frac{1}{2} \beta_{i-1,i-1}N_{i-1}N_{i-1} - N_i \sum_{j=1}^{i-1} 2^{j-i} \beta_{i,j}N_j - N_i \sum_{j=1}^{\text{max}} \beta_{i,j}N_j - S_iN_i + \sum_{j=1}^{\text{max}} b_{i,j}S_jN_j
\]

2.2 Computational fluid dynamics model

2.2.1 The geometric model. The geometry model in this study is based on the radial-flow secondary sedimentation tank of a wastewater treatment plant (WWTP) in Hefei with central inlet and peripheral outlet. The structure was partially simplified, and the influence of the scraper was omitted. The schematic diagram of the secondary sedimentation tank is shown in Figure 1.

2.2.2 The numerical model. In the second sedimentation tank simulation, the Euler model and the mixture model are both commonly used. As the most complex multiphase flow model in Fluent, the Euler model establishes independent momentum equations and continuous equations for each item which causes a large amount of calculation and is not easy to converge [20]. In this case, the process of polymerization and crushing of activated sludge particles are often simultaneous and the distribution of large-scale particle phase or interface is unknown. Thus a perfect Euler model is not suitable in this case. The mixture model is a simplified Euler model. The multiphase mixture was considered as a whole in mixture model, so the number of control equations and the calculation amount can be reduced. At the same time, this study focuses on the characteristics of the activated sludge mixed liquor rather than each single-phase. Therefore, the mixture model was selected in our simulation.

2.2.3 Model calibration and validation. The flow velocity distribution in the secondary sedimentation tank of the WWTP in Hefei was measured through MADV Acoustic Doppler flowmeters. The sections with radiuses of 5 m, 10 m and 15 m in the secondary sedimentation tank were selected as monitoring objects, and the velocity distribution on each section was measured in the vertical direction. As shown in Fig. 2, the results of the flow rate simulation in this study were in good agreement with the measured values and the distribution of the simulated values of the flow velocity on each monitoring section can
basically reflect the distribution of the velocity in the actual secondary sedimentation tank.

Figure 2: Comparison of the simulated and measured values of the flow rate on each monitoring section where R = 5 m (a), 10 m (b) and 15 m (c).

2.2.4 Parameter setting. We adjusted the internal structure of the flocculation well. As shown in Table 1 In the original flocculation well, five grid plates with a width of 25 mm and 35 mm were added along the flow direction. The spacing between two adjacent grid plates was 200 mm. In this article, we recorded the secondary sedimentation tank model with no grid, grid width of 25 mm and grid width of 35 mm as No.0, No.2.5 and No.3.5 model respectively.

Table 1: Layout of each grid flocculation well.

| Partition          | Size of grid (mm×mm) | Grid interval (mm) | Aperture ratio (%) |
|--------------------|----------------------|--------------------|--------------------|
| Front (Levels 1 and 2) | 50×50                | 25 (35)            | 44.4% (34.6%)      |
| Middle (Levels 3 and 4) | 70×70                | 25 (35)            | 54.3% (44.4%)      |
| Rear (Level 5)     | 80×80                | 25 (35)            | 58.0% (48.4%)      |

The influent flow rate of this simulation was 0.53 m s⁻¹, the sludge concentration was 5.8 g L⁻¹, the sludge viscosity coefficient was 0.0015 Pa s, the suspended matter density was 1180 kg m⁻³, and the water density was 998.8 kg m⁻³. We ignored the temperature exchange and set the inlet water temperature and operating temperature to 30 °C. According to the particle size distribution of activated sludge particles in the actual secondary sedimentation tank, the particle size distribution was discretized (The relationship between the particle size after dispersion and the particle number density was shown in Table 2). Assuming that the fluid in the pool was incompressible, the realizable k-ε model was used to simulate the flow characteristics. As for simulating the distribution of solid-liquid two-phase, the mixture model was utilized.

Table 2: Particle number density distribution of particles of different particle sizes in influent.

| Particle Size (μm) | 20  | 25  | 30  | 37  | 46  | 57  | 70  | 86  | 106 | 130 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Number density (10⁹ m⁻³) | 1.36| 1.19| 1.20| 1.75| 2.85| 3.28| 2.95| 2.89| 2.04| 1.73|

3. Results and Discussions

3.1 Flow state

3.1.1 Flow distribution in precipitation zone. As shown in Figure 3, there was a large vortex inside the
prototype of the second sedimentation tank (No. 0 model), which was quite different from the assumption of the ideal sedimentation tank. We set the monitoring section at a radius of 5 m (Y = 5 m), 10 m (Y = 10 m), and 15 m (Y = 15 m) respectively. At a water depth of 1-3.5 m and a radius of 5 m, there was a reverse flow in three models. The maximum reverse flow speeds of No.0 model, No. 2.5 model, and No. 3.5 model were 0.005 m s\(^{-1}\), 0.007 m s\(^{-1}\), and 0.003 m s\(^{-1}\) respectively. The reverse flow and bottom flow of sedimentation tank form the partial vortex and the area of the vortex core region of No. 2.5 model and No. 3.5 model were 80% and 42.9% of No. 0 model. At the monitoring sections with a radius of 10 m and 15 m, there was no obvious vortex in the upper part of the secondary sedimentation tank while in the sludge layer at the bottom, there was a reverse flow in the direction of the sludge bucket in the area close to the bottom of the tank (1 m above the bottom). In No. 0 model, this reverse flow extends from the flocculation well outlet to the vicinity of effluent. At a radius of 5 m, the rate of sludge reverse flow in the No. 2.5 model and the No. 3.5 model were respectively 2.3% and 26.2% lower than that in No. 0 model. At a radius of 10 m and 15 m, the sludge reverse flow at the bottom of No. 2.5 model disappeared, while the sludge reverse flow at the bottom of the No. 3.5 model still exist despite smaller region than that of No. 0 model.

![Flow rate vector of second sedimentation tank and radial velocity distribution on the axial monitoring section of where Y=5 m (a), 10 m (b) and 15 m (c).](image)

3.1.2 Flow distribution in flocculation wells. The radial monitoring sections were arranged separately to monitor the flow velocity distribution in the flocculation well at water depth 2.3 m (between the first layer and the second layer grid), 2.6 m (third layer grid), 2.9 m (between the fourth layer and the fifth
layer grid) and 3.1 m (flocculation well outlet). Due to the blocking of the grid plate, in the No. 2.5 and No. 3.5 models, the periodic distribution of high flow velocity and low flow velocity formed at the rear of the grid plate. However, the standard deviation of each monitoring section of No. 2.5 and No. 3.5 models were smaller than that of No. 0 model (Figure 4), and the average flow velocity on the outlet section were 86.4% and 90.9% of the flocculation well prototype respectively, indicating that the grid flocculation well could dissipate energy and homogenize the cross-section flow velocity.

![Figure 4: Mean velocity and unit volume kinetic energy of flocculation well monitoring section.](image)

In each flocculation well, the unit volume kinetic energy of the water flow was gradually reduced, and its reduction in the grid flocculation well was larger (No. 2.5 model and No. 3.5 model increase the energy dissipation efficiency of the prototype flocculation well by 40.1% and 55.6% respectively compared to No. 0 model), demonstrating better energy dissipation effect. When the influent passed through the grid plate in the flocculation well, the large-scale vortex was broken into small-scale vortices due to the inertia of the fluid and the turbulence of the grid. In the process of vortex breaking from large-scale into small-scale, the energy of large-scale vortex was also transmitted to small-scale vortex, and the lateral diffusion of fluid was enhanced. As the small-scale vortex increased, the viscous effect of fluid began to strengthen. Under viscous effect, the energy loss of the fluid increased. Furthermore, the viscous effects ultimately homogenized the flow velocity and activated sludge concentration distribution on the cross section, and at the same time enhanced the energy dissipation effect of the flocculation well.

3.2 Flocculation and precipitation study

3.2.1 Flocculation in flocculation wells. Figure 5 shows the distribution of the average volume fraction of activated sludge on different sections of each flocculation well model. In No. 0 model, the activated sludge in the flocculation well was mainly concentrated in the inner side while the concentration of activated sludge on the other side was very low, therefore the standard deviation was much higher than No. 2.5 and No. 3.5 models. This was mainly due to the difference in the concentration of activated sludge in the influent and in the secondary sedimentation tank, which led to the formation of density current in the flocculation well, so that the activated sludge could not disperse into the entire section in time. Thus, the distribution of activated sludge on the monitoring section was quite different. In No. 2.5 and 3.5 models, the density current were blocked and dispersed by the grid plate, which promoted the diffusion of activated sludge and the homogenization of volume fraction of activated sludge on each monitoring section in the flocculation well. An increasement was observed in the volume fraction of each flocculation well model along the water depth, and the flocculation effect of No. 2.5 model was the most obvious, indicating that a gradual polymerization process of the activated sludge existed in the flocculation well. The average volume fraction at the exit of the No. 0 model was 0.55% (sludge density
was 6.0 g L\(^{-1}\)), and for the 2.5 and 3.5 model were 0.76% and 0.64% respectively (sludge density were 8.4 g L\(^{-1}\) and 7.0 g L\(^{-1}\)), in which flocculation effects were better than the prototype.

![Figure 5: Average volume fraction of activated sludge in axial section of flocculation well.](image1)

![Figure 6: Particle size distribution of influent and effluent in flocculation wells.](image2)

As shown in Figure 6, after the influent passed through the flocculation well, the proportion of large particle size particles was notably improved. The proportion of the particles in the influent with size less than 98 μm was 53.2%. While in effluent, particles with size less than 98 μm of No. 0, No. 2.5 and No. 3.5 model accounted for 15.8%, 7.7% and 4.5% of the total particles respectively. Compared with the No.0 model, the volume fractions of the small particle size in effluent of No. 2.5 and No. 3.5 models were reduced by 50.9% and 71.5% respectively. After the grid plate was installed in the flocculation well, the energy consumed by the viscous effect provided power for the activated sludge flocculation. Therefore, the installation of the grid plate in the flocculation well provided good flocculation conditions for the activated sludge particles as well as increased the probability of collision and coagulation.

### 3.2.2 Solid-liquid separation

As shown in Figure 7, in the No. 0 model, a strong rising fluid was found in the area near the wall. The maximum flow velocity could reach 0.63 mm s\(^{-1}\), which was greater than the static sedimentation velocity of the sludge (0.48 mm s\(^{-1}\)). The suspended solids (with a concentration of 30 mg L\(^{-1}\)) which should be precipitated were transported to the surface due to this rising fluid, and finally reached the outlet, resulting in an increasing concentration of the suspended solids. In the No. 2.5 and No. 3.5 models, the upward flow velocity on the side close to the outlet were larger, and the average activated sludge concentration were 3.0 mg L\(^{-1}\) and 1.27 mg L\(^{-1}\). The rising fluid was mainly caused by the suction of the outlet of the secondary sedimentation tank. The water flow on the side close to the wall moved downward, and the activated sludge concentration were about 10.5 mg L\(^{-1}\) and 3.6 mg L\(^{-1}\). The rising fluid sludge concentration near the water outlet was low, while the downward flow sludge concentration near the wall was high, which was beneficial to the solid-liquid separation. The suspended solids concentrations at the outlets in No. 2.5 and No. 3.5 models were 16.9 mg L\(^{-1}\) and 7.3 mg L\(^{-1}\), respectively. The effluent activated sludge concentration of the second sedimentation tank prototype (23.9 mg L\(^{-1}\)) was reduced by 29.3% and 69.4%.
3.3 Actual optimization result

The WWTP secondary sedimentation tank was upgraded and No. 3.5 grid was added to flocculation well. After 5 days of start-up, the secondary sedimentation tank effluent was taken every two days to monitor the suspended solids (SS) concentration. During 30 days of the monitoring period (Figure 8), more than 85% measuring values of the effluent SS concentration were less than 10 mg L\(^{-1}\), with an average of 9.3 mg L\(^{-1}\), which was similar to the simulation result of 7.3 mg L\(^{-1}\). Compared with other un-optimized secondary sedimentation tanks, the effluent SS concentration was reduced by about 30%. Therefore, this optimization method could effectively improve the operating efficiency of the secondary sedimentation tank.

4. Conclusion

In this paper, the hydraulic properties of the secondary sedimentation tank and the flocculation and sedimentation process of activated sludge particles were simulated by the population balance model and computational fluid dynamics. The study found that the installation of the grid plate in the flocculation well could dissipate energy and homogenize the flow velocity of the section, increasing the probability of collision and coagulation of the activated sludge particles as well as providing good flocculation conditions for the activated sludge particles, resulting in the increasing proportion of large particle size particles in the activated sludge. The decrease of the effluent flow velocity of the flocculation well weakened the vortex phenomenon in the secondary sedimentation tank, provided good sedimentation conditions for the activated sludge particles, and obtained a better effluent. The final actual operation results were similar to the simulation results, indicating the effectiveness of the optimization method and the reliability of the simulation method.

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