Design, simulation, and laboratory test of a single sludge drainage pipe for wastewater treatment sedimentation tank

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ABSTRACT

This study develops a novel design scheme based on engineering fluid mechanics for the single-pipe-type sludge drainage mechanism of sedimentation tanks in the wastewater treatment industry. A laboratory-scale clarifier is fabricated for experimental verification. Sludge drainage ratio and suspended solids (SS) of inflow are selected as two factors for laboratory experiments, and SS values are measured to evaluate the performance of the sludge drainage pipe. Experiment data show that the designed single sludge drainage pipe can successfully achieve the supposed task with a coefficient of variation (CV) of SS less than 8.5%. The variation scope of CV from 1.5% to 8.3% suggests that the sludge drainage performance is relatively steady. Nine sets of 3D computational fluid dynamic (CFD) simulations, which is based on the inhomogeneous Eulerian–Eulerian multiphase model, were conducted for a comprehensive exploration and assessment. Results reveal noticeable deviations of the characteristics of the fluid in the outermost orifice of the sludge drainage pipe from the designed value. Although the fluid velocity through each orifice is matched with the designed values, the mass flowrate differs with a maximum of four times the designed value and a standard deviation of 0.4 of hole among the nine simulations. This study also suggests some considerations in the design process and routine operation of the single-pipe-type sludge drainage system.

Key words | 3D simulation, CFD simulation, design method, sedimentation tank, sludge drainage pipe

HIGHLIGHTS

- A design method for sludge drainage pipe, which is manageable for engineers and is adequately precise, is developed.
- The theory is verified through laboratory tests and 3D CFD simulations.
- Detailed geometry and nine simulations based on orthogonal experiment design theory are set in the simulation.
- Design and operational suggestions are proposed through ANOVA.
- Detailed simulations for the characteristics of fluids passing through the orifices are conducted and analyzed.

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INTRODUCTION

The single-pipe type sludge drainage device, which is equipped in a sedimentation tank in the wastewater treatment process for sludge drainage, uses only one or two structured pipes as the sludge drainage parts. This device exhibits considerable advantages over traditional vacuum suction or a scraping mechanism because of its simplified structure, rapid sludge drainage, and energy-efficient regulating method (Zhang 2007; Yang et al. 2012). In applications, more than 170 sets based on RIM-FLO® patented technique are adopted by medium to large-scale wastewater treatment plants around China; however, they have a higher investment than the traditional systems (Zhang 2007; Yang et al. 2012). The above-mentioned innovative mechanism is widely applied in municipal wastewater treatment plants and can be applied in industrial fields in the future if the theoretical design principles are clear and available to environmental engineers. Zhang (2007) introduced the process of installation, adjustment, and site test results of a real sedimentation tank that adopts RIM-FLO® technique for the first time in China. Thereafter, Yang et al. (2012) introduced a typical application of this patented technique in an activated sludge process. Most contents of the two investigations and other related studies have been focused on the performance and ability of the system, while a small amount of information about the related design theory has been revealed due to the complexity of the system (Zhang 2007; Bürger et al. 2012; Yang et al. 2012; Su et al. 2019).

In substance, the theory is related to fluid mechanics when concerning the design mechanism of the sludge drainage pipe. However, it is complicated because the governing equations have too many variables that need to be solved. Thus, the technique of computational fluid dynamics (CFD) can be applied for the simultaneous solving of equations, and many experimental and theoretical explorations have used the CFD technique for the sedimentation tank. These studies are characterized by a clear visualization of ‘factor effect,’ which is displayed on a micro- and macroscale for the traditional structure of a sedimentation tank (Bürger et al. 2012; Su et al. 2019; Xu et al. 2020). These investigations have discovered the flow fields for the liquid and solids through simulation (Ye et al. 2011; Hu 2013; Su et al. 2019; Xu et al. 2020) and explored the effects of several essential structures and design parameters, such as inflow baffles (Bajcar et al. 2010; Shahrokhi et al. 2013; Tarpakou & Pantokratoras 2013; Wei et al. 2016) and inflow distribution structure (Shen et al. 2011; Hao & Shen 2012), on the flow fields for engineering design verification purposes. However, few reports are concerned not only about the scenario in which a scraper or some other sludge drainage devices are equipped but also on the operational status, the change in flow regime, and the consequences of this change. This study develops an alternative novel design method for the sludge drainage pipe based on the engineering fluid mechanics. A single sludge drainage pipe on the mentioned basis for a laboratory-scale clarifier is designed for demonstration. An experimental test is conducted for verification, and a 3D simulation is performed for a comprehensive exploration of the sludge drainage mechanism, which is vital for engineering design and application.

METHODS

Theory

A typical sedimentation tank, which is equipped with a single sludge drainage pipe, is shown in Figure 1. The tank is characterized by one or two perforated square pipes revolving around its vertical axis nearly above its flattened bottom surface. While the sludge drainage pipes are rotating, the precipitated particles in the sedimentation tank are driven by the static hydraulic pressure of the
sedimentation tank to flow into the square pipe with liquid through the orifices on it. The liquid-solid mixture flows along the square pipe to the center end of the pipe and out of the sedimentation tank. During this process, relatively slow rotation is required to avoid disturbance of the settled sludge particles, and an even sludge drainage is overemphasized. This setting will incur another prerequisite, that is, a perfect influent distribution system for liquid and particles. This system is important for most engineers.

For verification, we use a laboratory-scale clarifier for designing, simulation, and testing. The top view of the supposed clarifier is illustrated in Figure 2. The clarifier is 435 mm in diameter and equipped with one radial stretched, square sludge drainage pipe. The design process can be accomplished through four steps as follows.

Step 1: The initial number of sludge drainage orifices on the pipe is determined. An arbitrary number is set according to the general rule of thumb as the initial step. Few orifices will lead to excessive pressure losses, disturbance of settled sludge, and non-dischargeable sludge. The distance between the orifices could be referred to decide the initial numbers of orifices, and can be as large as 1,000 mm in practice (usually 500 mm–1,000 mm). However, too many orifices will cause sedimentation of sludge (particles) inside the drainage pipe. In this case, four orifices are considered. Thus, the bottom of the sedimentation tank can be divided into four areas, namely, 1, 2, 3, and 4, according to the four evenly distributed orifices. As demonstrated in Figure 2, the distance between the orifices is 40 mm, and the three boundary circles of the four bottom areas fall evenly between the adjacent orifices. Alternative schemes of arrangement, such as adjusting the radial position of the orifices to achieve four equal bottom areas, will also be applied. After the arrangement of orifices on the pipe is determined, the supposed service area of the bottom of the clarifier corresponding to each orifice is ascertained accordingly.

Step 2: The size of the sludge drainage pipe is determined. When suspended fluid flows in a pipe, deposition may occur. The velocity sufficient to prevent deposition in a pipe flowing full; that is, self-cleansing velocity, can be approximated as

$$V_{\text{min}} = \sqrt{\frac{8B}{f} \frac{g}{(s-1)}D_p}$$

(1)

where $V_{\text{min}}$ – self-cleansing velocity, m/s; $B$ – dimensionless constant, 0.8 for adequate self-cleansing; $f$ – friction factor, dimensionless, 0.02–0.05; $g$ – gravitational acceleration, 9.81 m/s$^2$; $s$ – specific gravity of the sludge/particle; $D_p$ – diameter of the particle, m.

The particle diameter of activated sludge flocs varies widely and is difficult to determine. This parameter is affected by many factors. The typical value reported is generally between 50 and 500 μm (Wang 1998; Zhao 2011) and can reach approximately 0.2–2 mm (Tchobanoglous et al. 2014). In this case, an experiment is conducted to determine the diameter of activated sludge, which is taken from a clarifier of a local food factory for a sedimentation test. A laser particle size analyzer BT-9300H is adopted for the measurement. The results are shown in Figure 3. The red line represents the particle percentage of corresponding particle size, while the blue line represents the cumulative percentage. The median position diameter of sludge particles is around 60 μm, but a larger value of 0.5 mm (the maximum value in the abscissa in Figure 3) is taken in this design for safety. The minimum theoretical velocity in the sludge discharge pipe can be estimated as 0.18 m/s.

If an ideal operation scenario is achieved, that is, the single sludge drainage pipe can exactly collect all the settled particles during revolution, then the flowrate needed for each orifice can be calculated under the assumption that each orifice only collects its corresponding pre-planned serving area on the bottom of the clarifier (White 2016), that is,

$$Q_i = (V_i + \omega L_i)A_i = \varphi A_i \sqrt{\frac{2}{\rho} \left( \frac{p_i - p_s}{\rho} \right)}$$

(2)
where \( i \) – orifice number, which starts from the outermost part of the pipe to the inner part, 1, 2, …., \( n \); \( Q_i \) – flowrate of \( i \) orifice on the pipe, \( \text{m}^3/\text{s} \); \( V_i \) – average fluid inflow velocity through orifice \( i \), \( \text{m}/\text{s} \); \( \omega \) – rotation speed of the sludge drainage pipe, 1.83 in this case, \( \text{rev/min} \); \( L_i \) – horizontal distance from the bottom center of the clarifier to the center of the orifice \( i \), \( \text{m} \); \( A_i \) – area of orifice \( i \), \( \text{m}^2 \); \( q \) – orifice coefficient, 0.97–0.98 and should be corrected by measurement on site; \( p_i \) – static pressure in the horizontal plane of the orifices' center, \( \text{pa} \); \( p_{i-1} \) – static pressure inside orifice \( i \), \( \text{pa} \); \( \rho \) – density of liquid-solid mixture (sludge) near the sludge drainage pipe, \( \text{kg}/\text{m}^3 \).

We can draw the hydraulic diameter of the pipe segment, as shown in Figure 2, from the outermost segment 1, that is,

\[
d_{ii} = \frac{4 \sum Q_i}{\pi V_{\text{min}}} \tag{3}
\]

where \( d_{ii} \) – hydraulic diameter of the pipe segment; subscript \( ii \) – pipe segment with the same flowrate inside, \( \text{m} \); if one calculates the flowrate of the third pipe segment, we need to add \( Q_1, Q_2 \), and \( Q_3 \) together.

Step 3: The size of the first pipe segment and orifice is determined. After a set of initial process operational parameters is given for the sedimentation tank, we can determine \( Q_1 \) first and then \( d_{11} \). In this case, we assume that the hydraulic load of the clarifier is 1.0 \( \text{m}^3/\text{m}^2 \cdot \text{h} \) and the amount of suspended solids (SS) of the influent is 5,000 \( \text{mg} / \text{L} \). If the clarifier captures 80% of the SS of the influent, then we can determine that \( d_{11} \) is 6.0 mm × 6.0 mm (according to Formula (3), the first segment of the sludge drainage pipe). When the size of the first orifice \( d_1 \) is determined, we can choose an inflow velocity from the minimum (0.18 m/ s, determined by Formula (1) and lower value will prevent the orifice from inhaling sludge from a wide area) to the maximal value (1.5 m/s in this case, higher value will cause disturbance of the settled sludge). Here, we set \( d_1 = 5.0 \text{mm} \) according to this principle. For large and medium-sized sedimentation tanks, iteration is necessary to determine whether the initial setting value is appropriate. We can resolve the pressure difference from outside to the inside of the first orifice from Formula (2), as follows:

\[
p_{ii} - p_{i-1} = \frac{Q_i^2}{2 \rho A_i^2} \tag{4}
\]

where \( p_i = \rho g H \); \( H \) – water depth of the sedimentation tank, \( \text{m} \).

Step 4: The remaining dimensions of pipe segments and orifices are determined. When the sludge (solid–water mixture) flows along the inside of the sludge drainage pipe, friction and local losses will occur. This occurrence can be approximated for laminar flow from orifice 1 to orifice 2 (White 2016), that is,

\[
p_{i-1} - p_2 = p_{i-1} - \left( p_1 - \rho g \left[ \sum_{l=1}^{2} \left( \frac{64}{\text{Re}_i} \frac{l_i}{2d_{ii}} \frac{V_i^2}{2g} \right) + \xi \left( 1 - \frac{A_{22}}{A_{11}} \frac{V_2^2}{2g} \right) \right] \right) \tag{5}
\]

where the first term in the middle brackets is the friction loss, while the second term is local loss for a sudden enlargement of the sludge drainage pipe at the conjunction location between segments 1 and 2. \( \text{Re}_i \) – fluid Reynolds number of pipe segment \( i \); \( l_i \) – length of pipe segment \( i \), \( \text{m} \).
$V_{ii}$ – average fluid flow velocity inside pipe segment $i$, m/s; 
$\xi$ – coefficient of local loss, 0.2–0.5, and should be measured on site for accuracy; 
$A_{ii}$ – inner side section area of pipe segment $i$, m$^2$.

On the basis of $V_{1i}$, $A_{1i}$, and $Q_{1i}$, we can calculate $Q_2$ from step 1, and $V_{2i}$ can be approximately equal to $V_{1i}$. Similarly, $d_{2i}$ can be determined from Formula (3), and $A_{2i}$, $Re_1$, and $Re_2$ can be determined. From Formula (4), $p_1$ can be solved. Accordingly, we can solve $p_t-p_4$ from Formula (5) and $d_2$ from Formula (2). At this time, the parameters of pipe segment 2 are completed.

By repeating step 4, we can determine the parameters of pipe segment 3 by analyzing the laminar flow from orifice 2 to orifice 3, as follows:

$$p_1 - p_3 = p_t - p_4 \approx \frac{p_2 - p_4}{2g} \left( \sum_{i=2}^{3} \frac{64}{Re_i} \frac{V_{2i}^3}{2g} + \xi \left( 1 - \frac{A_{2i}}{A_{22}} \right) \frac{V_{22}^2}{2g} \right)$$

(6)

On the basis of this mechanism, we can design to the last pipe segment, pt-p4, which is the most central part of the single sludge drainage part. The inside pressure p4 of orifice 4 is close in value to the drainage pressure of a sedimentation tank and can be manually regulated by the discharge valve via water level. Thus, from the aspect of the operation, we can predict and determine the sludge discharge performance of the sedimentation tank by solving Formula (5) backward; that is, from pipe segment 4 to pipe segment 1.

Accordingly, we can establish a preliminary design for this case shown in Table 1 and Figure 4. If any unrealistic or infeasible results appear, then we should re-conduct the four steps until a more feasible design is obtained.

**Laboratory experiment**

The designed single sludge drainage pipe is fabricated and installed into a PMMA-made clarifier, as described above. The experiment keeps the hydraulic load of the clarifier constant to 1.0 m$^3$/m$^2$·h. Influent pump, and influent SS and sludge drainage rates are subject to change during the experiment. SS of the mixture fluid at the identical height of the center of the orifices in the sludge drainage pipe (h = 13 mm) is sampled via a pipette (un-tapped, 50 mL) and measured in accordance with the Chinese national standard (GB11901-89). As depicted in Figure 2, 18 sampling points are allocated on the imaginary horizontal plane with 13 mm above the bottom of the clarifier (small circles in Figure 2) and are sampled every 30 min during the operation of the clarifier. This operational experiment lasts 2 h each time and is repeated three times. Thus, a specific sample point has 12 SS measurements in all for one experiment’s setting, and these measurements are averaged in records. Some of the results are listed in Tables 2 and 3. For overall evaluation, this experiment also includes two extreme operational statuses: no sludge drainage from the clarifier and no influent running. The contrast is illustrated in Figure 5.

Table 2 shows that the SS concentrations on sample areas varies. Meanwhile, the solid (dry sludge)

**Table 1** | Design specification of the sludge drainage pipe of the clarifier

| Pipe segment $i$ | 1   | 2   | 3   | 4   |
|------------------|-----|-----|-----|-----|
| Length of pipe segment $i$/mm | 40  | 40  | 40  | 57.5|
| Outer dimension of pipe $i$/mm | 10.0×10.0 | 10.0×10.0 | 10.0×10.0 | 10.0×10.0 |
| Inner dimension of pipe segment Ødi/mm | 6.0×6.0 | 7.5×7.5 | 8.5×8.5 | 0.0×9.0 |
| Diameter of orifice Ødi/mm | 5.0  | 2.6  | 2.0  | 1.7  |

**Figure 4** | Geometry structure of the sludge drainage pipe for analysis (Section view, arrows stand for flow direction of sludge).
concentration of the influent, or the influent sludge load, is modulated to three levels: 3,000, 4,000, and 5,000 mg/L. During this experiment, the inflow hydraulic load and bottom sludge drainage rate are maintained at 1.0 m³/m²·h and 50% drainage, respectively. A total of 50% drainage means that the sludge drainage rate is 0.5 of the influent.

Table 3 exhibits the variation in SS concentration when the influent rate is 1.0 m³/m²·h, the SS concentration is 2,000 mg/L, and the sludge drainage rate is changed at three levels; namely, 50, 70, and 90% of the inflow rate.

As for the influent distribution, many investigations have been conducted to improve an even sludge sedimentation pattern on the bottom of the tank (Shen et al. 2014; Hao & Shen 2015). However, as depicted in Figure 5 (left figure), when the single sludge drainage pipe remains static and the sludge drainage valve (beneath the bottom of the clarifier) remains closed, distinct uneven distribution pattern of solid sedimentation is observed. This condition will cause great concern for the design of the sedimentation tank for the time being and is an unfavorable factor or failure-leading factor. However, during the running status, the rotation of the sludge drainage pipe will homogenize the sedimentation evenness. This deduction can be obtained from the coefficient of variation (CV) of columns from Tables 2 and 3. In the operation of the three cases, no considerable sludge accumulation appears among 18 sample points. The CVs vary from 1.5% to 4.0% when the SS concentrations are 3,000, 4,000, and 5,000 mg/L. Meanwhile, the values are from 6.2% to 8.3%, which are all less than 10.0%, when the sludge drainage ratios are 0.5, 0.7, and

### Table 2 | Measured SS values on the bottom layer of the sedimentation tank with different sludge loads (Inflow hydraulic load: 1.0 m³/m²·h, Bottom sludge drainage rate: 50% drainage)

| Influent SS/ mg/L | 3,000 | 4,000 | 5,000 |
|-------------------|-------|-------|-------|
| Average SS value of sample points 77.5 mm away from center/mg/L | 6,645 | 7,125 | 9,515 |
| Average SS value of sample points 117.5 mm away from center/mg/L | 6,870 | 7,340 | 9,675 |
| Average SS value of sample points 157.5 mm away from center/mg/L | 7,130 | 7,715 | 9,810 |
| Average SS value/mg/L | 6,882 | 7,393 | 9,667 |
| Coefficient of variation | 3.5% | 4.0% | 1.5% |

### Table 3 | Measured SS values on the bottom layer of the sedimentation tank with different sludge drainage ratios (Inflow hydraulic load: 1.0 m³/m²·h, Solid concentration of the influent: 2,000 mg/L)

| Percentage of drainage to influent rate | 50% | 70% | 90% | Coefficient of variation |
|----------------------------------------|-----|-----|-----|--------------------------|
| Average SS value of sample points 77.5 mm away from center/mg/L | 4,175 | 3,085 | 2,660 | 23.6% |
| Average SS value of sample points 117.5 mm away from center/mg/L | 4,560 | 3,305 | 2,670 | 27.4% |
| Average SS value of sample points 157.5 mm away from center/mg/L | 4,830 | 3,635 | 2,960 | 24.9% |
| Average SS value/mg/L | 4,522 | 3,342 | 2,763 |
| Coefficient of variation | 7.3% | 8.3% | 6.2% |
The statistical data of grids are 167.78% for maximum face angle, 53.58° for minimal face angle, 1 to 24.9 for edge length ratio, and 1 to 421.05 for element volume ratio for densely meshing control in small areas and regions where fluid field changes significantly. The single sludge drainage pipe is built as a separate domain in geometry and uses domain motion in simulation.

The influent raw mixture can be described as liquid (water)–solid (sludge) two-phase flow theoretically given that the air dissolved in the aeration basin is negligible compared with the sludge. Liquid/water is the continuous phase and solid/sludge is the dispersed one; the behavior of the two phases is governed by the inhomogeneous Eulerian–Eulerian multiphase model (Ansys Inc. 2009) other than the homogeneous one, because the solid phase exhibits a different sedimentation process. The mathematical governing model includes a momentum equation, continuous equation, volume conservation, pressure constraint, and total energy equation (Ansys Inc. 2009).

Momentum equation (Ansys Inc. 2009):

\[
\frac{\partial}{\partial t} (r_\alpha \rho_\alpha \mathbf{U}_\alpha) + \nabla \cdot (r_\alpha (\rho_\alpha \mathbf{U}_\alpha \otimes \mathbf{U}_\alpha)) = -r_\alpha \nabla p_\alpha + \nabla \cdot (r_\alpha \mu_\alpha \nabla \mathbf{U}_\alpha) + \left( \sum_{\beta=1}^{N_p} \left( (\Gamma_{\alpha\beta} \mathbf{U}_\beta - \Gamma_{\beta\alpha} \mathbf{U}_\alpha) + S_{M_{\alpha\beta}} + M_{\alpha\beta} \right) \right)
\]

where \( \nabla = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \); \( \alpha \beta \)— different phases of fluids in lowercase; \( r_\alpha \)— volume fraction of phase \( \alpha \); \( \rho_\alpha \)— density of phase \( \alpha \), kg/m³;
\( \mathbf{U}_\alpha \)— velocity vector of phase \( \alpha \), m/s;
\( \mathbf{U}_\beta \)— velocity vector of phase \( \beta \), m/s; \( \nabla \)–Hamilton operator; \( \otimes \)–vector production operation;
\( p_\alpha \)– static pressure of phase \( \alpha \), Pa; \( \mu_\alpha \)–molecular (dynamic) viscosity of phase \( \alpha \), Pa·s;
\( N_p \)–number of phases; \( (\Gamma_{\alpha\beta} \mathbf{U}_\beta - \Gamma_{\beta\alpha} \mathbf{U}_\alpha) \)– momentum transfer induced by interphase mass transfer; \( \Gamma \)–divergence operator; \( S_{M_{\alpha\beta}} \)–momentum sources due to external body forces and user-defined momentum sources; \( M_{\alpha\beta} \)–interfacial forces acting on phase \( \alpha \) due to the presence of other phases.

The sludge particles act as a dispersed phase in the continuous phase of water and can be simulated by particle mode (Ansys Inc. 2009). When assuming the sludge particle \( \beta \) a spherical ball, it will be acted upon by the continuous fluid \( \alpha \), which can be described as follows (Ansys Inc. 2009):

\[
M_{\alpha\beta} = M^{D}_{\alpha\beta} + M^{L}_{\alpha\beta} + M^{LB}_{\alpha\beta} + M^{VM}_{\alpha\beta} + M^{TD}_{\alpha\beta} + M_{\alpha\beta} \cdots
\]

where \( M^{D}_{\alpha\beta} \)–total interfacial force; \( M^{D}_{\alpha\beta} \)–drag force; \( M^{L}_{\alpha\beta} \)–lift force;
Simulation initialization and setup

The simulation scenarios, which are a supplement to the laboratory experiments and for an overall assessment, are set according to experimental design theory. The simulation setup includes three variants: surface influent load (Inload), pressure difference pt-p4 (dP), and rotation speed of the sludge drainage pipe (REV). After determining the variation range of the three variants, the simulation can be designed following the orthogonal experimental design table L9 (34) (Li & Hu 2017), which is listed in Table 4. The initial setup of the simulation model is listed in Table 5.

RESULTS AND DISCUSSION

The above-mentioned governing equations are solved by a CFD software package Ansys CFX® with the initial settings listed in Table 5. Nine scenarios configured in Table 4 are considered. The drawn typical results are listed in Table 6 and depicted in Figures 6–10.

Figure 6 shows a comparison between some typical simulated data and measured ones of the nine experiment sets. Three varieties, namely, sludge concentration in mg/L of the clarifier’s effluent, sludge concentration in mg/L of the sludge drainage pipe’s effluent, and sludge mass flowrate in kg/h of outflow from the sludge drainage pipe, are simulated and measured for the nine cases. The results for the nine tests are depicted in Figure 6 with statistical bars in three groups. In each group, the left bar represents the measured statistical data, and the right bar represents the simulated one. The mean values between the measured data and the simulated ones are very close for each group. The 3D CFD approach can provide a reasonable prediction. The sludge concentration of the effluent of the tested clarifier remains relatively stable among the nine tests, and this condition suggests a steady and reliable performance of the clarifier. By contrast, the sludge mass flowrate of the sludge drainage pipe varies considerably according to the operational conditions and exhibits a noticeable mean value difference between the measured data and the simulated ones. The reason may be that the measurement process is averaged and all the settled sludge masses (not

Table 4 | Configuration of the simulation scenarios

| Test no. | dP/mmH2O | REV/rev/min | Inload/m³/(m²·h) |
|----------|----------|-------------|------------------|
| 1        | 1/100    | 1/0.1       | 3/1.6            |
| 2        | 2/350    | 1/0.1       | 1/1.0            |
| 3        | 3/550    | 1/0.1       | 2/1.3            |
| 4        | 1/100    | 2/0.05      | 2/1.3            |
| 5        | 2/350    | 2/0.05      | 3/1.6            |
| 6        | 3/550    | 2/0.05      | 1/1.0            |
| 7        | 1/100    | 3/0.04      | 1/1.0            |
| 8        | 2/350    | 3/0.04      | 2/1.3            |
| 9        | 3/550    | 3/0.04      | 3/1.6            |

Table 5 | Some initial condition, parameters, and settings of the simulation

| Item in model | Setting in this paper |
|---------------|-----------------------|
| SS concentration of influent | 4,000 mg/L |
| Sludge particle | Ø50 μm, 1,050 kg/m³ |
| Ambient | 25 °C, 101,325 Pa |
| Liquid/solid pair coupling model | Interphase transfer: Particle Model |
| Lift force | Saffman Mei Model |
| Virtual mass force: Coefficient 0.5 |
| Wall lubrication: Antal Model |
| Turbulent dispersion force: Favre Averaged |
| Turbulent transfer: Satio Enhanced Eddy Viscosity Model |
| Momentum transfer: Gidaspow Mass transfer: No |
| Model for dispersed particle | Kinetic model |
| Radial distribution function: Gidaspow |
| Buoyancy model | Density Difference Model |
| Turbulence model | Solid phase: Dispersed Phase Zero equation Model |
| Solid pressure model: kinetic Model |
| Solid bulk viscosity: kinetic Model |
| Liquid phase: K-epsilon |
| Buoyancy turbulence: P&D |
| Wall function: Scalable |
| Turbulence initials | Medium (5%) |
| Wall model | No-slip |
| Solving method | Finite volume method, fully implicit multi-grid coupled solution |
| Solving scheme | High resolution, double precision |
| Convergence iteration | RMS, 0.00001 |
| Iteration parameters | Step: 200 s/200 s, number of steps: 300 |
dry) are divided by the whole experiment time. On the contrary, the simulated one is a short period averaged steady-state value. However, frequent operational measures should be taken in routine operation or a more stable design method should be developed further.

As validation and comparison, Zhang (2007) tested a full-scale RIM-FLO clarifier (fabricated by U.S. Filter) of 36 m in diameter and 4.5 m in depth, he measured the SS of the clarifier’s effluent and found that the SS is below 30 mg/L when the surface load varies from 1.0 m$^3$/m$^2$.h to 2.0 m$^3$/m$^2$.h, and the MLVSS of the influent varies from 3,512 mg/L to 3,910 mg/L. Yang et al. (2012) reported that for more than 170 sets of RIM-FLO clarifiers in China (22 m–50 m), the design value of SS of clarifier’s effluent is below 20 mg/L when the influent surface load varies from 1.0 m$^3$/m$^2$.h to 1.5 m$^3$/m$^2$.h. From Figure 6, it can be found that the SS of the clarifier’s effluent is below 16 mg/L (measured) and 18 mg/L (simulated) with an influent surface load variance of 1.0–1.6 m$^3$/m$^2$.h.

### Table 6 | Comparison of simulated and designed characteristics per orifice of the tested drainage pipe

| Test no. | Designed Mass flowrate ratios of liquids passing through the four orifices Ori. 1: Ori. 2: Ori. 3: Ori. 4 | Simulated | Flow velocity ratios of liquids passing through the four orifices Ori. 1: Ori. 2: Ori. 3: Ori. 4 | Simulated | Sludge volume fraction ratios of liquids passing through the four orifices Ori. 1: Ori. 2: Ori. 3: Ori. 4 | Simulated |
|---|---|---|---|---|---|---|
| 1 | 5.7:2.8:1.3:1 | 10.1:3.0:1.4:1 | 1.0:1.1:1.0:1.0 | 1.4:1.0:0.7:1.0 |
| 2 | 10.1:3.0:1.4:1 | 10.1:3.0:1.4:1 | 1.3:1.3:1.0:1.0 | 2.6:0.9:1.1:1.0 |
| 3 | 10.1:3.0:1.4:1 | 9.7:3.0:1.2:1 | 1.3:1.2:0.9:1.0 | 0.7:1.2:0.6:1.0 |
| 4 | 3.8:1.8:1.3:1 | 10.1:3.0:1.4:1 | 1.3:1.3:1.0:1.0 | 2.4:1.3:0.9:1.0 |
| 5 | 1.3:1.3:1.0:1.0 | 1.1:0.7:0.6:1.0 |
| 6 | 1.3:1.3:1.0:1.0 |
| 7 | 2.3:1.3:0.8:1.0 |
| 8 | 1.3:1.3:1.0:1.0 |
| 9 | 1.3:1.3:1.0:1.0 |
| Standard deviation | 2.7:0.1:0.1:0.0 | 0.4:0.1:0.1:0.0 | 3.2:1.5:0.3:0.0 |

### Figure 6 | Comparison between simulated and measured characteristics of the tested clarifier (Data were organized into three variable groups. The left statistical bar stands for the measured data and the right for the simulated data for each group).
For detailed exploration of the performance of the sludge drainage pipe, Table 6 lists some parameters among the four orifices in ratios compared with the design values. During the design process, equal suction velocity value is assigned to each orifice, that is, the velocity ratio between orifices 1, 2, 3, and 4 is 1:1:1:1. At the same time, the CFD results, as listed in Table 6, show that reasonably good agreement is achieved in eight tests (the standard deviation is less than 0.1) of nine, and the design method exhibits excellent compatibility in the first step. However, the first orifice should be given attention because it differs the most from the others.

The same flow velocity can stand for the same volume flowrate if the fluids flow through the same area of orifice, but the case is not true for the mass flowrate because the sludge fraction in the flow can vary dramatically. Table 6 shows that mass flowrate through the first orifice deviates from the supposed design value more than three times in test 7, whereas good agreements are obtained for the others. Meanwhile, the first orifice of the pipe also changes considerably in the mass flowrate with a standard deviation of 2.7. The reason is that the sludge volume fraction (not the absolute dry sludge) in the flow changes considerably, as shown in Figure 6. It changes more than 10 times the supposed sludge fraction flow through the first orifice in test 7 and is much subjected to the changes in the operational conditions (with a standard deviation of 3.2).

The design method is based on the same flow velocity setting and the assumption that the mass flowrate of the settled mixture (sludge) will behave accordingly. The CFD simulation shows that it applies most of the situation besides the first orifice. At the outermost orifice of the sludge drainage pipe, a noticeable deviation occurs and varies violently with the operational conditions of the clarifier. This situation suggests that a further mechanism that can determine the sludge volume fraction in the flow should be developed to improve the design to an ideal status.

Figure 7 depicts the water velocity vector profile on the plane 13 mm above the bottom of the clarifier (Test No. 5).
the sludge drainage orifices are on (the sludge drainage pipe rotates counterclockwise). Visible movement pattern could be found that the settled fluids fan out, at lower velocity, into the clarifier from the spots under the influent pipe of the clarifier. When combined with Figure 8, one can know for sure that the streamline (flow path) of the settled fluids exhibits the ideal sludge flow path supposed to avoid shortcut (Zhang 2007; Yang et al. 2012; Tchobanoglous et al. 2014). The velocity inside the sludge drainage pipe is much higher than that outside, which could prevent the re-rising of the settled sludge, and this meets the design requirements substantially. However, a noticeable variety of velocity could be seen inside the sludge drainage pipe, this could give rise to, although in the same order of magnitude, the dramatic variation (listed in Table 6) of the sludge flowrate through each orifice. Among the four sludge drainage orifices, the flow velocity through the outermost one (orifice 1) is nearly at the same level as the other three, but the diameter is the largest and that is why orifice 1 has the maximum flowrate. Another phenomenon that needs to be considered is that the flow velocity inside the sludge drainage pipe varies obviously, which deviates from the design setting and need alternative design plans for optimization.

Figure 9 demonstrates the sludge volume fraction pattern on the plane 13 mm above the bottom of the clarifier, and the basic profile is the evenly distributed sludge volume fraction, this partially indicates an ideal design configuration. Whereas three significant exception regions (not ideal) occurred, the first one is that the sludge volume fraction inside the sludge drainage pipe, outside part from orifice 2, is lower than that in the outside counterpart layer, this could be explained by less compression for the outside two orifices than for the inner two because of having fewer tributaries; the second region is adjacent and just before the sludge drainage pipe, for the outer the segment part of the pipe, the faster the segment part moves, which would disturb the settled sludge more.

Figure 10 shows the interaction effect matrix of three operational parameters, namely, dP, Inload, and REV, to the mean square deviation of the four orifices’ mass flowrate of the sludge drainage pipe. The mean square deviation is calculated from the square mass flowrate deviation from the design value for each orifice, and the sum is averaged. Figure 7 is based on the analysis of variance (ANOVA) (Li & Hu 2017) of the simulated data. As observed, the sludge drainage pressure dP will affect the sludge drainage performance most: a low level (350 mm H2O) and a high level (550 mm H2O) in operation will result in a steady and ideal sludge drainage condition and less deviation from the design status despite the variation in the two other factors, namely, REV and Inload. When the sludge is drained under moderate pressure, 350 mm H2O in this case, a remarkable fluctuation will occur according to the variation in Inload and REV. Moderate inflow hydraulic load or slow revolving speed will deteriorate the sludge drainage situation. On this basis, low inflow hydraulic load, fast revolving speed, and high sludge drainage pressure are appropriate settings for the pre-designed operating situation. However, in all settings of this simulation, the sludge is drained successfully with no accumulation on the bottom or in the effluent.
Under the operational situation, if a designed status needs to be achieved, then a combination of high revolving speed and moderate sludge drainage pressure or low revolving speed and high sludge drainage pressure will be preferred for low inflow hydraulic load. When the inflow hydraulic load rises to a moderate level, a combination of high sludge drainage pressure and high revolving speed of pipe or low sludge drainage pressure and high revolving speed is preferred. In the case of high inflow hydraulic load, low revolving speed with low sludge drainage pressure or high sludge drainage pressure is recommended.

CONCLUSIONS

In this study, a method based on engineering fluid dynamics is developed to design a single sludge drainage pipe in a peripherally inflow and outflow sedimentation tank. A laboratory-scale clarifier is designed accordingly and fabricated for performance verification. Some conclusions can be drawn from the simulation as follows.

With appropriate inflow hydraulic load for the tested clarifier, the single sludge drainage pipe can successfully accomplish the supposed task in the limited laboratory test. When the SS in the influent and the volume flowrate of sludge drainage vary, the designed single sludge drainage pipe functions properly with the CV of measured SS values less than 8.5%. The variation scope of measured SS’s CV is from 1.5% to 8.3%, which suggests that a relatively steady running status is obtained.

During the laboratory test, the revolving sludge drainage pipe can homogenize the unevenly settled sludge particles. Therefore, the energy loss of orifice pattern should be given more attention than the influent distributing system, which is emphasized by engineers at present.

In a further CFD 3D simulation exploration, characteristics inside the sludge drainage pipe are simulated and analyzed. The velocities through each orifice can meet the designed value, with a maximum standard deviation of 0.4 from orifice 1 during the nine simulations. The mass flowrate exhibits a significant deviation of more than four times the designed value for orifice 1 as the three variants change.

The dynamics of sludge particles should be studied meticulously to improve the design method because they behave differently in flowing through the orifices and cause volume fraction differences between orifices. The deviation of mass flowrate from the design value maintains the supposed volume flowrate.

The outermost orifice in the sludge drainage pipe is mostly subjected to deviation from the design value when the operational parameters change. Therefore, low inflow hydraulic load, fast revolving speed, and high sludge drainage pressure are appropriate settings to the pre-designed operating situation in this study.

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DATA AVAILABILITY STATEMENT

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

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