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Large-eddy simulations of particle sedimentation in a longitudinal sedimentation basin of a water treatment plant. Part 2: The effects of baffles

M. Al-Sammarraee, A. Chan*

School of Chemical and Environmental Engineering, University of Nottingham (Malaysia Campus), Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia

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ABSTRACT

The process of particle sedimentation in a three-dimensional longitudinal basin with vertical baffles in a water treatment plant is studied using large-eddy simulations (LES). The objective of this study is to investigate the effect of the baffle installations on the particle settling performance of the sedimentation basin. The fluid mixture simulates typical contaminated water in which the contaminants are represented by a spectrum of 13 different particle sizes. The process of sedimentation of all classes of particles is simulated for tanks with zero, two, three and four baffles, respectively. The flow patterns, particle settling velocities, the particle settling efficiency and volume fraction are computed using LES and a multiphase model. The overall sedimentation efficiency of the basin for all the cases is calculated.

Results show that the installation of baffles would effectively improve the performance of the tank in terms of settling. The baffles act as barriers and effectively suppress the horizontal velocities of the flow and force the particles to the bottom of the basin. Turbulence and vortices are generated at the shear zones near the baffles which significantly increase the settling velocity.

The effect of varying number of baffles on the settling is also studied. Results indicate the performance of the basin increases with increasing number of baffles. The more the number of baffles the larger the suppression of the horizontal velocities and more chances the particles are forced to the bottom. The number of small eddies formed at the bottom of the basin also increases with the number of baffles. These results are important for the cost-effective design of longitudinal sedimentation basin in water treatment plants.

1. Introduction

Sedimentation tanks are one of the most important components and the workhorses of any water treatment plants. It is crucial for the sedimentation tank to operate at its full potential. It is not only the physico-chemical aspects of flocculation that is important, hydraulics plays a prominent part in its performance [1,2]. Overdesign due to lack of knowledge of hydraulics in sedimentation tank is common, leading not only to unnecessary capital and operating expenditure, but also to water wastage in the form of excessive sludge. Improper and inadequate design cause overloading of filters, and lead to frequent backwashing, which in turn waste a significant percentage of treated water. Since treatment tanks last a few decades, most do not incorporate the latest developments in technology to deal with these issues [3–5]. Therefore, good understanding of the various hydraulic processes within water treatment is essential for good design for long term use.

Particle and contaminant removal is the key process in any water treatment plant. Many different attempts had been made to increase the performance of particle removal in sedimentation basins. In order to improve particle settling efficiency, a number of strategies have been reported, such as installation of baffles and porous plates [5,6]. Goula et al. [6] studied the particle settling in a sedimentation tank using a vertical baffle installed in a circular sedimentation tank inlet section and showed that the baffle increased the particle settling efficiency from 90.4% for a standard tank without baffle to 98.6% for one with baffle installed.

Fan et al. [2] studied the hydrodynamic and settling effects of including baffles at different locations in a secondary circular sedimentation tank with baffles of two different lengths. They observed that the solid concentration profile in the flow region near the baffle was similar to that obtained without baffle. In contrast, the solids concentration increases sharply in the outer region of the baffle, which suggests that the solid phase congregates rapidly at the end of the baffle. Fan et al.'s work [2] has provided good evidence that the inclusion of the baffle is favourable to the accumulation of solid phase. They also found that as the baffle distance from the centre is increased, the solid phase is more ready to congregate in the outer region of the baffle.

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* Corresponding author. Tel.: +60 3 89248144; fax: +60 3 89248017.
E-mail address: andy.chan@nottingham.edu.my (A. Chan).

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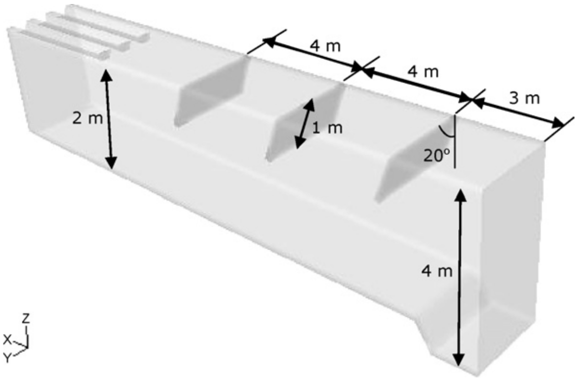

Fig. 1. Longitudinal sedimentation basin geometry with baffles.

Recently many research works had employed computational fluid dynamics (CFD) techniques to model the processes within different wastewater sedimentation tanks units in order to predict the fluid flow patterns and particle dispersions during each phase along these tanks. Shamber and Larock [7] used a finite volume method to solve the Navier–Stokes equations, the k–ϵ model and a solid concentration equation to model settling in secondary clarifiers. Fan et al. [2] studied the flow dynamics in a secondary sedimentation tank and modelled the solid–liquid two-phase turbulent flow in the tank by a three-dimensional two-fluid model. CFD simulations were also used to analyse the sediment transport for multiple sediment sizes and to estimate the efficiency of solid removal in a raceway [8]. Results as such can be used to estimate the efficiency of the whole process.

In view of the seemingly attractive evidence that baffles can improve the particle settling efficiency significantly, we would like to study the effect of baffles in a longitudinal sedimentation basin. However the specific design requirements regarding baffles installation have not been addressed. For instance, the ideal locations and numbers of baffles are questions remained unanswered. These results would provide important insights to the engineers for the design of water treatment plants. It is in this area that we would like to insert an effort into.

In this part of the study, we would like to study the efficacy of baffles in improving the particle settling performance of a longitudinal sedimentation basin. This work is a sequel of a previous work [9] in which we studied the particle sedimentation process of a realistic longitudinal basin under construction. The longitudinal sedimentation tank that is be used in this simulation is similar to the one in a previously reported work [9] except with a little modification on the design to compensate for the inclusion of the baffles. The increase of depth in the sedimentation tank is not expected to affect the particle removal as long as the overflow rate is maintained the same [10].

2. Methodology

2.1. Computational grid of longitudinal sedimentation basin with baffles

The geometry of the longitudinal sedimentation basin with baffles is illustrated in Fig. 1, showing the different sizes and densities for the vertical baffles installed in the sedimentation basin. The total volume of sedimentation basin is equal to 280 m^3, 20 m in length and 3 m in width; the length of the outlet weir is equal to 5 m with 0.6 m width. The tank bottom had a slope of 4°, while the sump section near the inlet zone (the place where the sludge accumulates) is equal to 1 m deep. The tank is based on a real tank as in [9] which the location cannot be disclosed due to contractual reasons.

Tetrahedral mesh had been used with approximately 110,000 cells: the average mesh size is around 0.3 m, reducing to 0.05 m near the walls. The boundary conditions for the inlet flow (influent) is mass-inlet and for the outflow (effluent) is pressure-outlet. As in [9], the basin is considered full of water and devoid of a free surface.

In this study we would like to study the effect of the geometric configurations on the particle settling efficiency of the sedimentation basin. Two types of variations would be studied: in Case I we would like to study the effect of baffles on the sedimentation process and compared its performance with that without baffles. In Case II, the number of the baffles would be varied and its effects on the particle settling and the sedimentation process would be studied.

2.2. Large-eddy simulations

The governing equations of LES are obtained by filtering the time-dependent Navier–Stokes equations in the physical space [11]. The filtered Navier–Stokes equations are

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \bar{u}_j \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j^2} - \frac{\partial \tau_{ij}^r}{\partial x_j} - g\boldsymbol{k}, \tag{2}$$

where $\bar{u}_i$ is the filtered velocity of the ith component, x_i is the coordinates of the ith direction, t is the time, ρ is the fluid density, $\bar{p}$ is the filtered pressure, ν is the kinematic viscosity of the fluid, τ_{ij}^r is the residual stress tensor and g is the gravitational acceleration along the vertical downward direction, denoted as $\boldsymbol{k}$.

Turbulence closure is achieved through the static Smagorinsky's model [11]

$$\tau_{ij}^r = 2^{3/2}(C_S \Delta \overline{S_{ij}})^2 \tag{3}$$

where C_S is the Smagorinsky constant (∼0.17), Δ is the filter-size of the grid and $\overline{S_{ij}}$ is the rate of strain tensor.

2.3. Particles

The inlet flow consists of two phases: the primary phase is water and the secondary phase is particles. The particles are divided into 13 classes based on the diameter of the particle which would be described in detail later. The simulation process had been made for each particle class as a secondary phase.

The particle concentration at the entrant of the sedimentation basin is 1000 mg/ℓ, the corresponding water inlet velocity (volumetric flow rate over sedimentation basin cross sectional area perpendicular to the flow) equals to 0.0014 m s^{-1} along the basin. The effective density of the particles and water is 1066 kg m^{-3} and 998.2 kg m^{-3}, respectively. The condition of slip velocity between the two phases had been neglected since there is only a minute difference between the densities of the two phases [2]. In longitudinal sedimentation tank sludge will be drawn intermittently from the sump section, and thus no consideration for the presence of sludge is made [7,12].

To model the two-phase flows, a mixture approach is taken [12–14]. The mixture model is a simplified multiphase model that can be used to model multiphase flows where the phases move at different velocities, but assuming local equilibrium over short spatial length scales. The coupling between the phases should be strong. The mixture model simulates phases (fluid or particulate) by solving the momentum, continuity, and energy equations for the mixture, the volume fraction equations for the secondary phases, and algebraic expressions for the relative velocities.

Table 1
Particle classes of flow in the sedimentation basin [6].

Particle class	Mean diameter (μm)	Mass fraction	Mass flow rate (kg s^{-1})
1	20	0.025	0.00125
2	50	0.027	0.00135
3	80	0.039	0.00195
4	120	0.066	0.0033
5	170	0.095	0.00475
6	200	0.115	0.00575
7	250	0.126	0.0063
8	350	0.124	0.0062
9	450	0.113	0.00565
10	550	0.101	0.00505
11	650	0.077	0.00385
12	750	0.057	0.00285
13	850	0.04	0.002
Total		1.00	0.05025

2.4. Numerical simulation

A flow of water at 180 m^3/h is introduced as an inlet flow to the sedimentation basin. The inlet flow consists of two phases: the primary phase being water and the secondary one being solid particles. The secondary phase (particles) is divided into 13 classes according to the diameter of each particle as illustrated by Table 1. The simulation process had been made for each particle class as a secondary phase. The classification is based on raw water data measured using laser diffraction technique [6].

The mass flow rate in kg s^{-1} of each class of particles had been estimated. The computations are performed using the commercial code FLUENT (Release 6.3.26). In longitudinal sedimentation tank the sludge will be drawn intermittently from the sump section and thus no consideration for the presence of sludge will be made in the equations to adjust the settling performance [2,12].

The segregated unsteady solution algorithm with bounded central differencing is selected to solve the continuity and the momentum equations. Second-order upwind is used to calculate the volume fraction for the particle concentration.

3. Particles settling efficiency

We look at the immediate effect on the installation of the baffles to the sedimentation process in the tank. In this basic design as illustrated as in Fig. 1, three baffles are installed at equi-distance from each other in the sedimentation tank. This design is typical of many existing tanks [2,4]. Particles settling efficiency (%) for each individual class had been estimated (Table 2) by computing the mass flux of particles in the inlet and outlet streams, respectively. Fig. 2 illustrates the settling efficiencies of particles for the original tank (without baffles) [9] and tank with baffles for different particle diameters.

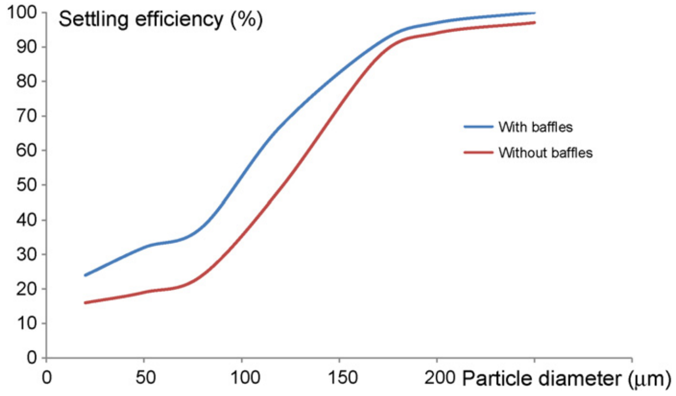

Fig. 2. Settling efficiencies of particles for the original tank (without baffles) and tank with baffles.

The total particle settling efficiency (%) for the longitudinal sedimentation basin had also been estimated. For convenience only particle Classes 1–7 will be studied since the settling efficiency of the remaining heavier particle classes is equal to 100% even without the baffles [9]. The inclusion of the vertical baffles in the sedimentation basin will not affect the settling efficiency of these particles.

It is clear that the particle settling efficiencies for respective Classes 1–7 are significantly improved especially for small size particles (20 μm, 50 μm, 80 μm, and 120 μm). The total settling efficiency for longitudinal sedimentation basin has increased from 87.1% to 91%. In fact this portion of increase (4%) could be more because the main increase occurs with the smaller particles (Class 1–4), which had a relatively small mass fraction in the sampled water. Fig. 2 also suggests that the sedimentation efficiency for individual particles is not correlated with the particle size.

An explanation had been made by Goula et al. [6] for the effect of vertical baffles on increasing the settling efficiency of particles for circular tanks. In general, the extended baffles appear to provide better influent mixing and isolation between the sedimentation tank influent and effluent than that in the original tank (without baffles) design and thus it improves sedimentation significantly. In addition, it allows a better utilisation of the full tank depth than in the standard design (without baffles) that leads to better separation between the influent and effluent along the vertical direction. Their results show that an extended baffle forces the solids to move faster towards the bottom of the tank and decreases the inlet recirculation zone, thus yielding significantly enhanced sedimentation. Fan et al. [2] stated that in the region near the baffle, the contour of solid concentration differs sharply from that without the baffle. The inclusion of the baffle is beneficial for the accumulation of solid phase. By comparison of different tanks with different baffle locations, it is observed that the solid concentration in the outer region increases with the ascendant radial location of the baffle. The effect at a location lower than the baffle is stronger than when above the baffle. Our results agree with what was obtained in circular sedimentation basins [2].

4. Flow pattern

A mid-plane is created inside the sedimentation tank to analyse the hydrodynamics of the fluid mixture within the basin. The particle settling velocity in the *z*-direction had been estimated through a line started from the sedimentation tank inlet zone (bottom) and extended to the outlet weirs (outlet zone) as in [9] and [12].

Simulations have been conducted for the entire spectrum of particle sizes. For display purposes only particles of sizes Class 1 (20 μm) and Class 5 (170 μm) are shown (Table 2). As discussed the larger classes all settle quickly with or without baffles and will not be shown. Figs. 3–6 display the volume fractions, velocities contours, velocities vectors, particle settling velocities and mixture turbulence contours for the sedimentation tank for the afore-mentioned particle sizes.

Figs. 3–9 show the hydrodynamics for Class 1 particles. Comparisons with [9] show that the presence of baffles prevent the dispersion of the light particles at the top of the basin. Particles are rapidly drawn near the bottom or the sump through the blockage of barrier. As seen in Figs. 3 and 4, the amount of volume fraction that is able to settle at the sump is significantly larger than that without baffle. From Figs. 5 and 6, it can be seen that the velocity profile is more complicated than the basic design without baffles. Two major vortices are formed between the first and the second baffles which significantly increase the vertical particle settling velocity in these areas as compared to the case without baffles [9]. A vortex is also

Table 2
Particle settling efficiency (%) and total settling efficiency (%).

Particle class	Mean particles diameter (μm)	Mass fraction	Settling efficiency (%), original tank	Settling efficiency (%), with baffles	Improvement (%)
1	20	0.025	16	20	25.0
2	50	0.027	19	24	26.3
3	80	0.039	24	31	29.2
4	120	0.066	49	68	38.8
5	170	0.095	87	96	10.3
6	200	0.115	94	97	3.2
7	250	0.126	97	99	2.1
Total		0.493	73.8	80.3	8.8

formed near the exit weir through mixing. These vortices are created by the turbulence generated by the baffles as illustrated in Fig. 7.

Fig. 8 shows the particle settling velocity as measured using by methods by Al-Sammarraee et al. [9] and Micale et al. [16]. In spite of the complexity of the flow pattern, the trend of the pattern of the particle settling velocity is similar to that without baffles. The particle settling starts to appear slightly beyond the sump area, where the settling is very slow, and increases as it gets near the exit weir as in Fig. 9. The settling velocity is significantly higher than the case without baffle with explanations given before. The settling velocity again appears at 5 m away from the inlet because very close to the inlet the settling velocity is infinitesimally small.

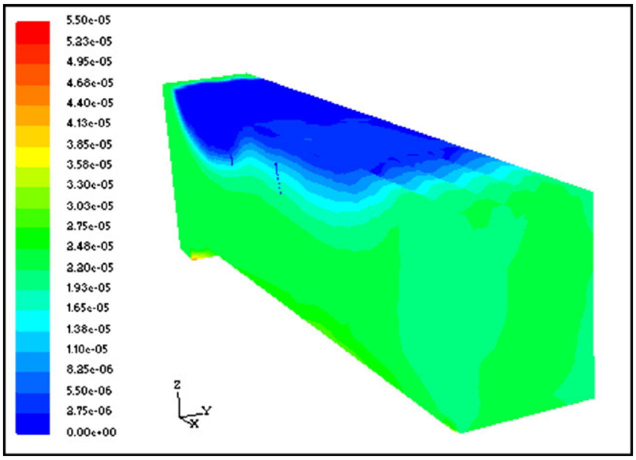

Fig. 3. Volume fraction contour of fine particles (Class 1) top view.

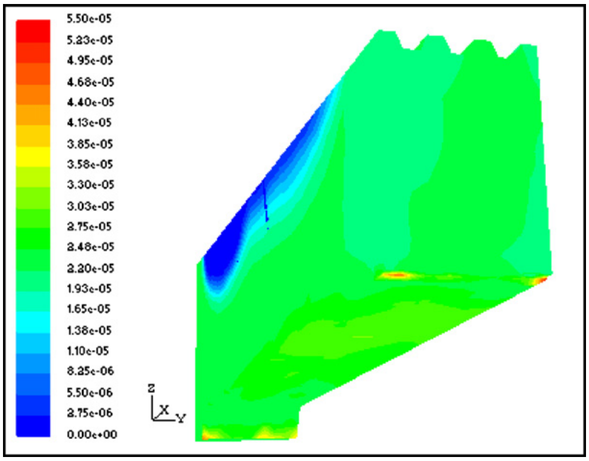

Fig. 4. Volume fraction contour of fine particles (Class 1) bottom view.

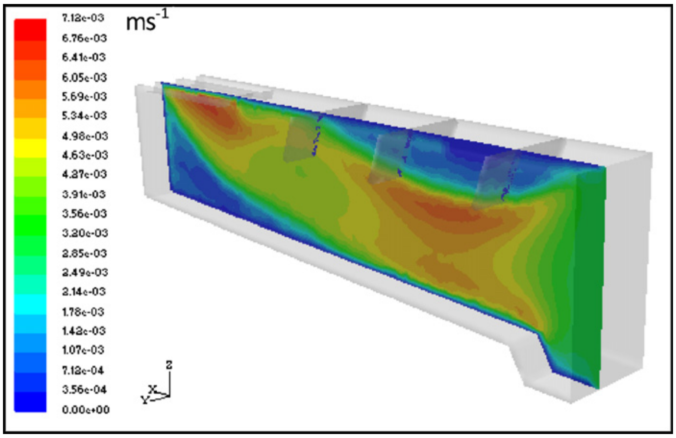

Fig. 5. Velocity magnitude contour of fine particles (Class 1).

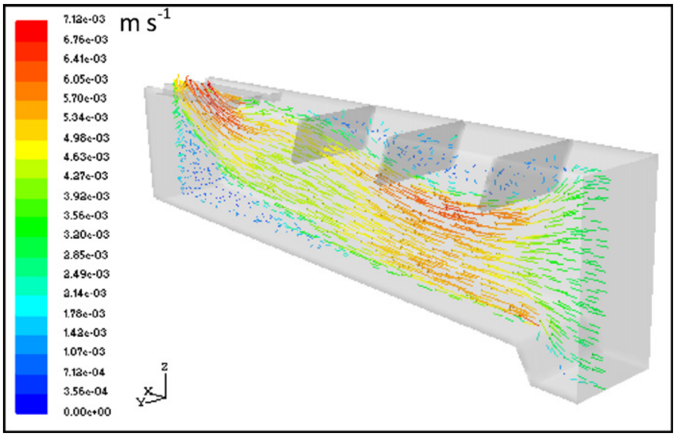

Fig. 6. Velocity vectors of fine particles (Class 1).

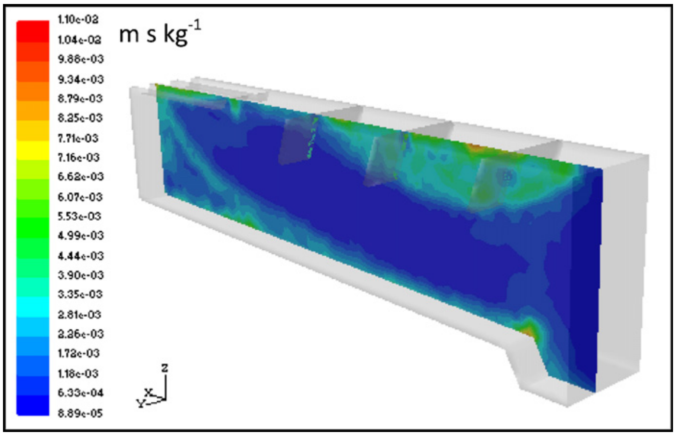

Fig. 7. Subgrid turbulent viscosity contour of fine particles (Class 1).

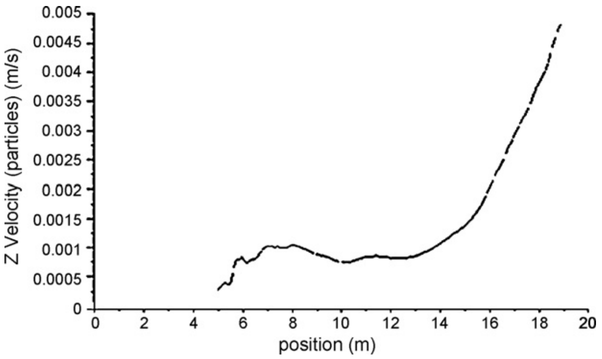

Fig. 8. Particles settling velocity along the sedimentation tank (Class 1).

Figs. 10–13 show the dispersion of Class 5 (medium-sized) particles. Compared to the case without baffles, it is clear that the baffles have improved the settling even for the medium-size particles [9]. Fig. 10 shows that volume fraction of medium-sized particles that settled at the bottom of the basin.

Fig. 11 shows the velocity contour of the medium-sized particles inside the basin. It can be observed that the vortex is much more extended than the case of the fine particles, meaning larger portion of the particles are enclosed within the vortex and prevented from drifted away by the flow. The lower location of the vortex also indicates these particles are concentrated nearer to the bottom than the fine particles. Fig. 12 shows the turbulence intensity of the plots and it is clear the turbulence is generated near the bottom and at the sump of the basin. The particle settling velocity is shown in Fig. 13.

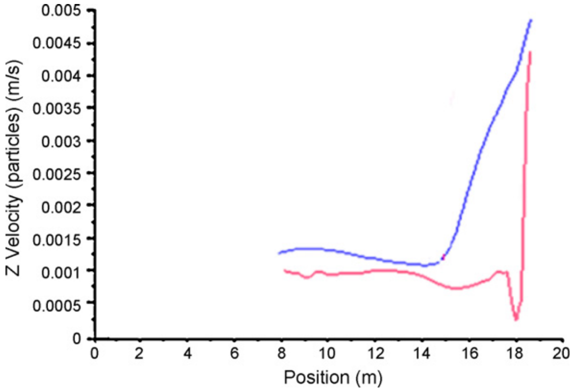

Fig. 9. Particles settling velocities distribution for fine particles along the basin (Class 1) (pink no baffle; blue with baffles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

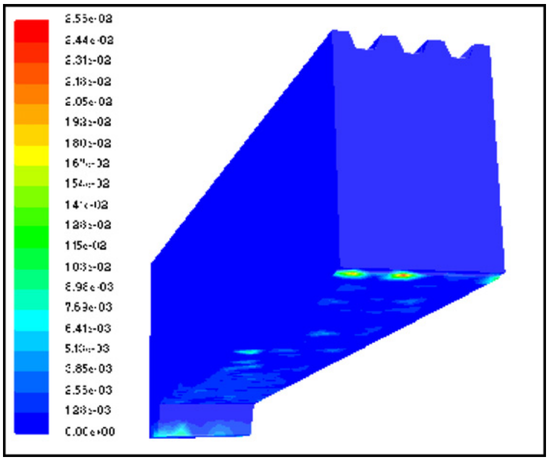

Fig. 10. Volume fraction contour of medium-sized particles (Class 5) bottom view.

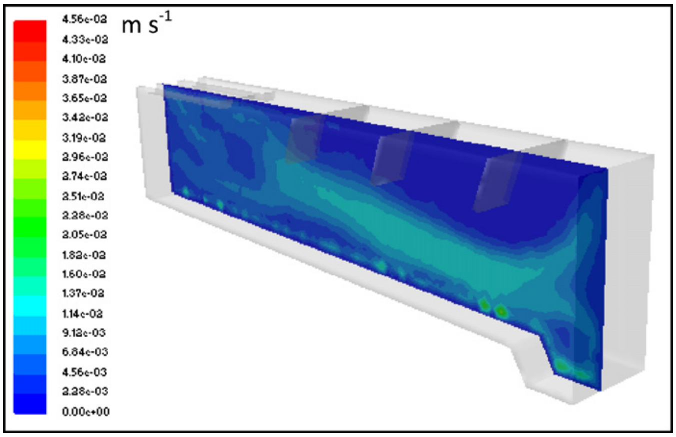

Fig. 11. Velocity magnitude contour of medium-sized particles (Class 5).

Figs. 3–13 clearly show that the baffles divert the direction of particles toward the bottom of the tank and let them settle easily. These figures show the main reason of the increase in particles settling efficiency. Moreover the settling velocities of particles increase along the sedimentation tank from top to bottom, and their magnitudes are significantly larger that of the original sedimentation tank without baffles (Fig. 9). Moreover the presence of baffles reduces the turbulent eddy size to that between the gaps of the baffles and near its shear zones. The presence of baffles also reduces significantly the horizontal velocity and helps settling through reduction of kinetic energy and turbulence [15].

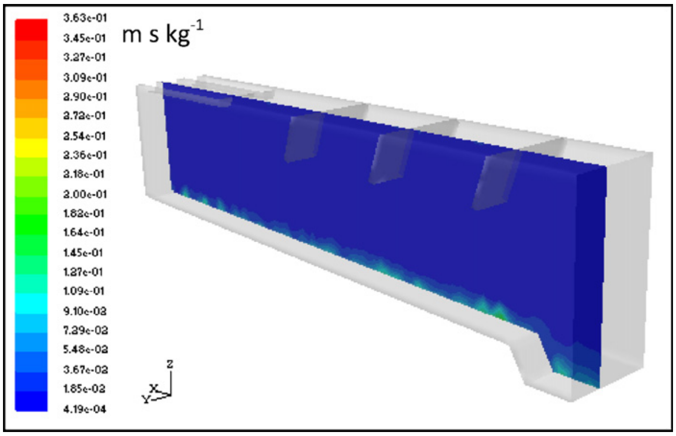

Fig. 12. Subgrid turbulent viscosity contour of medium-sized particles (Class 5).

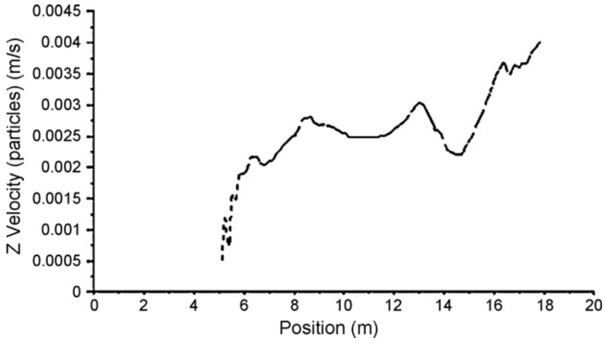

Fig. 13. Particles settling velocity of medium-sized particles along the basin (Class 5).

Table 3
Settling efficiency for sedimentation basin for 2–4 baffles, bracket showing percentage improvement over original tank.

Class	Two baffles	Three baffles	Four baffles
1	18 (12.5%)	20 (25.0%)	25 (56.3%)
2	21 (10.5%)	24 (26.3%)	38 (100.0%)
3	28 (16.7%)	31 (29.2%)	46 (91.7%)
4	57 (16.3%)	68 (38.8%)	76 (55.1%)
5	90 (3.4%)	96 (10.3%)	99 (13.8%)
6	95 (−1.1%)	97 (3.2%)	100 (6.4%)
7	98 (−1.0%)	99 (2.1%)	100 (3.1%)
Total	76.5 (3.7%)	80.3 (8.8%)	85.1 (15.3%)

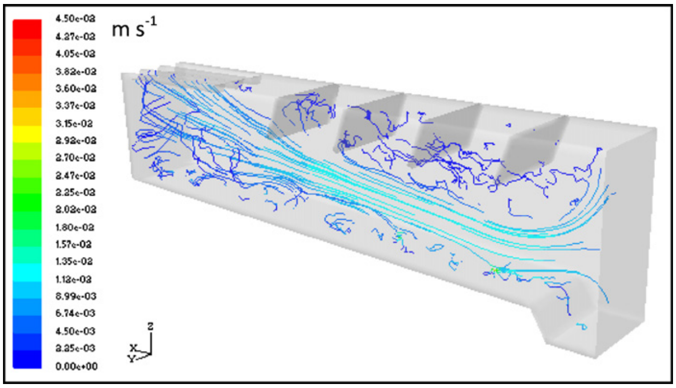

Fig. 14. Particles velocity path lines for Class 5 particles in a 4-baffle basin.

It is worth mentioning that even little difference in the settling velocities of particles will lead to significant increase in the settling efficiencies. Studies by Goula et al. [6] and McCorquodale and Zhou [15] showed the importance of a baffle in dissipating the kinetic energy of the incoming flow and in reducing short-circuiting. They indicated that the location of the baffle has a pronounced effect on the nature of the flow. The lower the kinetic energy dissipation rate, the more intense is the recirculation zone. The extended baffle increases the kinetic energy and the dissipation rate in the inlet baffling region and as a consequence weakens the currents in this region [15]. In the same manner Figs. 7 and 12 show the turbulent motions near the baffles which increase rapidly compared to other regions in the flow field. From these two figures and the previous findings the role of baffles in increasing the kinetic energy and dissipation rate in order to suppress the currents nearby which leads to better settlings of particles [6,15]. Additionally, particles velocities increase suddenly after hitting the vertical baffles (Figs. 6 and 11) which throttle the incoming flow and force it to pass through a narrow area underneath.

5. Baffle numbers

We would now study the effect of the number of baffles on the particle settling in the basin. From a design point of view, it is important to know the optimum number of baffles for settling, so that the basin is neither over nor under-designed.

As mentioned in Section 2.1 simulations are made for three types of longitudinal sedimentation basins to study the effect of the baffle numbers. We study the case for two, three and four baffles based on the capacity of the basin. Only the Class 1–7 particles are shown as the settling efficiency of larger sized particles is 100% regardless. Table 3 shows that the settling efficiencies for these tanks increase with the number of baffles. For fewer numbers of the baffles, the baffle arrangement forces the particles to hit the tank bottom and entrain by the flow. The particles are then carried away to the outlet weir instead of settling inside the tank. This is substantiated in Figs. 14 and 15 where the pathlines for Class 5 particles for the case of four and three baffles are shown. These two figures demonstrate the intense particle interactions near the tip of baffles. In fact the fewer the baffles, the larger the extent of turbulence generated, which makes settling more difficult. On the other hand, the denser the baffles, the more the particles are being suppressed to the bottom, and the more unlikely for the particles to flow back into the entrainment zone. This can be shown in Figs. 14 and 15 where a lot of small vortices are observed near the basin bottom which trap particles.

Dufresne et al. [17] showed experimentally that particles deposits in the central zone of a sedimentation tank are regularly resuspended but cannot escape because they are jailed by the vortices inside the tank. This phenomenon is confirmed by our numerical experiments, where turbulence generated near the bottoms is holding the particles. The baffles help to create these small vortices and thus help sedimentation and suspension. For the case with three baffles the flow resembles a rotary flow in the centre of the tank which caused by the inclusion of baffles whereas in the case for no baffles, the streamline has no curvature motion and running smoothly to the end of the tank then excite from the outlet weir.

Fig. 16 plots the settling efficiency of different particle sizes for the case of two, three and four baffles. As explained the larger number the baffles, the more intensive the vertical motions and smaller the horizontal motions. It is also obvious that the settling efficiency increases with the size of the particles. Intuitively the more the number the baffles, it simply means the depth of the tank is smaller and particles are quickly forced to the bottom of the tank. From a design point of view, obviously a very large number of baffles is infeasible.

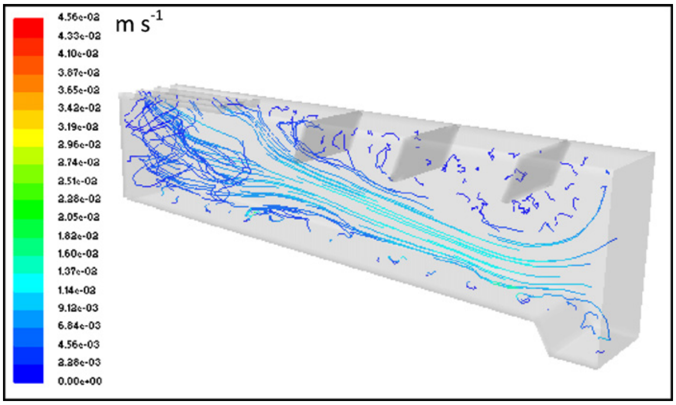

Fig. 15. Particles velocity path lines for Class 5 particles in a 3-baffle basin.

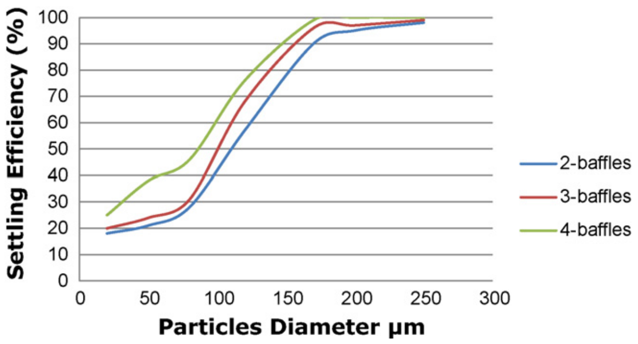

Fig. 16. Settling efficiency for different particles in sedimentation basin with two, three and four baffles.

6. Conclusions

The process of particle sedimentation in a three-dimensional longitudinal basin with vertical baffles in a water treatment plant is studied using large-eddy simulations. The fluid mixture mimics typical contaminated water in which the contaminants are represented by a spectrum of 13 different particle sizes. The process of sedimentation of all classes of particles is simulated for tanks with zero, two, three and four baffles, respectively. The flow patterns, particle settling velocities, the particle settling efficiency and volume fraction are computed using LES and a multiphase model. The overall sedimentation efficiency of the basin for all the cases are all calculated.

Results show that the installation of baffles would improve the performance of the tank in terms of settling. The baffles act as barriers and effectively suppress the horizontal velocities of the flow and force the particles to the bottom of the basin. Turbulence and vortices are generated which significantly increase the settling velocity.

The effect of varying number of baffles on the settling is also studied. Results indicated for the limited number of cases, the performance of the basin increases with increasing number of baffles. For fewer numbers of the baffles, the baffle arrangement forces the particles to hit the tank bottom and entrain by the flow. The particles are then carried away to the outlet weir instead of settling inside the tank. The more the baffles the larger the suppression of the horizontal velocities and more chances the particles are suppressed to the bottom. The number of small eddies formed at the bottom also increases with the number of baffles which assist in settling. These results are important for the cost-effective design of longitudinal sedimentation basin in water treatment plants.

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