Numerical Simulation on the Hydrodynamics of Sedimentation Tank When Longitudinal Inclined Plates Are Employed

Kirpa Hirom and Thiyam Tamphasana Devi

1 Introduction

The settling of suspended particles through gravitational force occurs in a sedimentation tank and can be regarded as a crucial step for the treatment process of any water treatment system. The difference in density between the sediments and the water forces the sediments to follow a deviated path from that of the water streamlines towards the bottom and eventually settle out. Gravity is the main driving force of this process. Sedimentation tanks of various shapes and sizes are employed at multiple stages of both the potable water treatment (PWT) and wastewater treatment (WWT) plants [1].

There is a certain type of compact sediment settler usually deployed at industrial wastewater facilities (especially for mining and metal finishing industries) where there is no luxury of space for installation of large sedimentation tanks that take advantage of these factors—called lamella clarifier. However, in terms of versatility, ease of use, and large-scale water treatment, conventional sedimentation tanks dominate over lamella clarifiers. Taking cues from the lamella clarifier, many researchers have tried to reap its advantages by modifying existing geometries of conventional sedimentation tanks with inclined plates. The superiority of these modified sedimentation tanks retrofitted with inclined plates has been proven through many studies [3–6]. However, only lateral inclined plates are used in all of these studies and very few on longitudinal inclined plates. With 3-D numerical studies becoming a norm in the past few years, future studies on the optimisation of sedimentation tanks are expected to follow in a direction similar to this research area. Therefore, in this study, the effectiveness of longitudinal inclined plates in increasing the efficiency as well as

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the improvement in the overall performance of the sedimentation tank is thoroughly investigated through 3-D numerical simulations.

2 Materials and Methods

2.1 Geometry and Meshing

The rectangular settling tank employed for this study has dimensions of 42.7 m * 11.5 m * 4.1 m (L * B * H) with the longitudinal inclined plates placed starting from 1 m away from the inlet baffle. A total of 25 longitudinal inclined plates of different surface areas are placed on each half of the sedimentation tank with an angle of 35° with respect to the horizontal and are 200 mm apart, as shown in Fig. 1. To support these inclined plates, three equally spaced support pillars are also installed right at the longitudinal centre line of the sedimentation tank, as shown in Fig. 2. This method of installing the inclined plates as two halves (rather than extending from one side wall to the other entirely, without any support pillars in the middle) was adopted to facilitate the movement of the settled particles onto the bed of the sedimentation tank for sludge removal. This would not have been possible if the inclined plates were placed from one side wall to the other since the inclination of the inclined plates will be very less and clogging can occur between the plates due to the settled particles. A gap of 500 mm is also maintained between the bottom end of the inclined plates and the bed of the sedimentation tank for the purpose of easier removal of these settled particles.

The geometry is divided into three regions—inlet, outlet, and mid-region—for a more efficient meshing, as shown in Fig. 3. Hybrid meshing is adopted for this study. The mid-region mainly comprises tetrahedron elements because of the addition

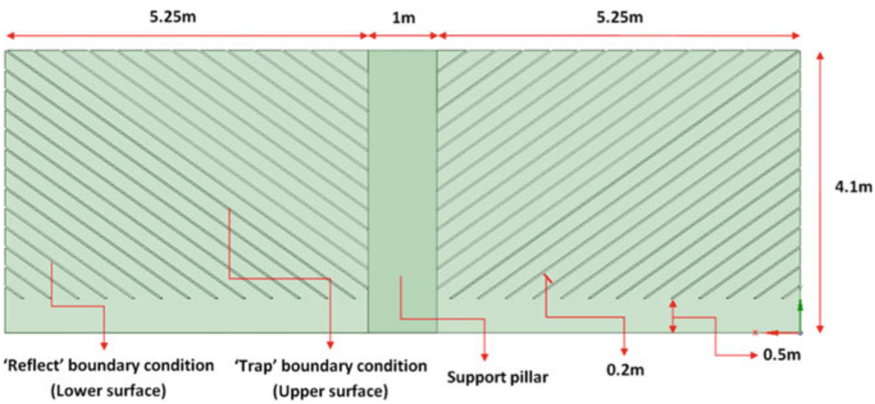

Fig. 1 Cross-sectional view of the new geometry at $z = 4.4$ m

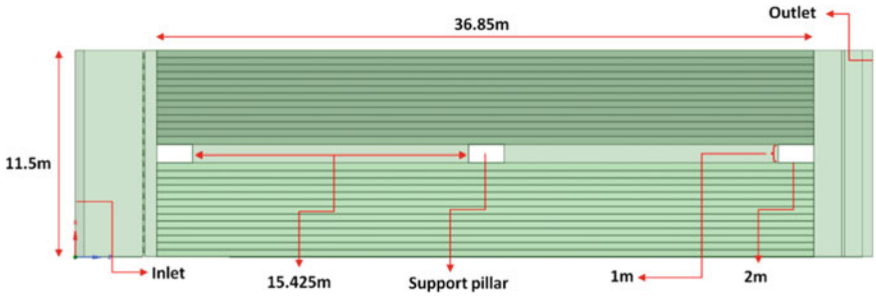

Fig. 2 Top-view of the new geometry

of inflation layers along the longitudinal inclined plates as well as the side walls and the bed of the sedimentation tank, to capture the boundary layer fluid flow more accurately. The inlet region and the outlet region mainly comprise the more economical and accurate hexahedron elements. The meshing of the geometries is performed using the Ansys meshing software.

The necessary grid-independence test was performed for this study by varying the ‘element size’ between 0.08 m and 0.5 m. The final selected value was 0.1 m since no significant change in solution was observed in further reducing the ‘element size’. A total of 10.44 million elements are present on the meshed geometry finally selected for simulation.

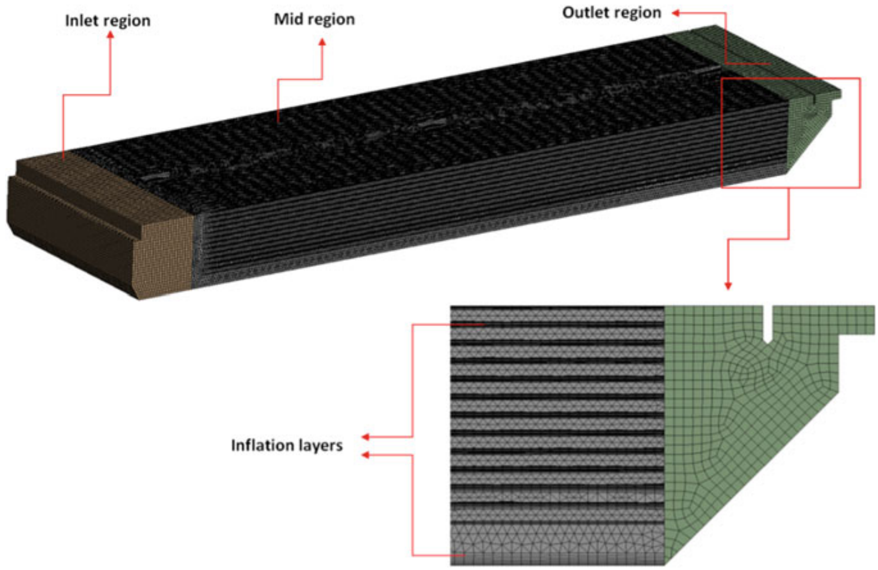

Fig. 3 The generated mesh for the modified geometry

2.2 Boundary Conditions

The inlet of the sedimentation tank is assigned as the ‘velocity-inlet’ boundary condition with 0.0281 m/s as the velocity magnitude. The primary phase (water), as well as the discrete phase (sediments), is discharged from the inlet surface at this velocity magnitude in the direction perpendicular to the specified inlet surface. As for the outlet, the ‘pressure-outlet’ boundary condition is assigned. ‘Symmetry’ boundary condition is assigned at the top of the sedimentation tank to model the zero-shear slip walls [8]. As for the inner surfaces of the sedimentation tank and the longitudinal inclined plates, the ‘stationary wall’ boundary condition is assigned with a ‘no-slip’ shear condition [9].

Additional boundary conditions specific to the DPM are required in order to decide the fate of the discrete particles when they come in contact with the boundary surfaces. The inlet and the outlet of the sedimentation tank are assigned the ‘escape’ boundary condition so as to allow free movement of the discrete particles through them. The bottom bed of the sedimentation tank and the upper surfaces of the longitudinal inclined plates (where sedimentation can take place) are assigned the ‘trap’ boundary condition. Any discrete particle that comes in contact with this boundary condition has its path terminated and its fate is reported as ‘trapped’ after the particle tracking process is completed. The ‘reflect’ boundary condition is assigned to the side walls of the sedimentation tank, the lower surfaces of the longitudinal inclined plates, and the inlet baffles. The discrete particles rebound off the surface when they come in contact with any surfaces with this boundary condition and continue on their path through the flow domain until it gets trapped or escaped.

2.3 Governing Equations

The governing equations are expressed as:

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

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{u_i}'\overline{u_j}'\right) \tag{2}$$

In the above equations, $u_i\mathrm{u_i}$ is the instantaneous velocity along $x_i\mathrm{x_i}$ direction; $U_i\mathrm{U_i}$ and U_j are the mean velocity along x_i and x_j directions, respectively; $\rho\rho$ is the density fluid; p is the static pressure; and ν is the kinematic viscosity of the fluid. The term $\overline{u_i}\prime\overline{u_j}\prime\overline{\mathrm{u_i}}'\overline{\mathrm{u_j}}'$ is solved using turbulence closure [10]. For this study, the $k - \omega$ SST (Shear Stress Transport) turbulence model is used since the geometries of our study comprise a good mixture of regions with near-wall region flows (when the longitudinal inclined plates are present), and free surface flow region (in the absence of the longitudinal inclined plates).

The model used in this study calculates the path of each discrete particle injected using the resultant of all the associated forces on each particle. The resultant force is calculated by equating the inertia of the particle with that of the outside forces acting on the discrete particle, as shown in Eq. (3).

2.4 Particle Size Distribution

For WWT, the particle size distribution of Vahidifar et al. [7], which was obtained through the Particle Size Analyst (PSA) test is used. As for the PWT, the particle size distribution of Goula et al. [11], which was obtained using the Laser Diffraction Analyser.

2.5 Settling Efficiency Calculation

The settling efficiency for a particular particle class (E_i) and the total settling efficiency for a particular case (E_{total}) are calculated using Eqs. (3) and (4).

$$E_i = \left(\frac{n_{i,trapped}}{n_{total}}\right) \times 100\% \quad (3)$$

$$E_{total} = \sum_{i=1}^{13} \frac{E_i \times Mf_i}{100} \quad (4)$$

In Eqs. (3) and (4), $n_{i,trapped}$ is the number of particles reported as trapped for the ith particle class; n_{total} is the total number of particles tracked, i.e. 26,724; Mf_i is the mass fraction for the ith particle class.

2.6 Solution Procedure

As mentioned before, the fluid mechanics problem is decoupled and the steady-state flow characteristics of the primary phase (water) are calculated before the calculation of the path of the discrete particles (sediments) in the flow domain. This is accomplished by first obtaining a steady-state flow field of the primary phase and then the discrete particles are ejected from the inlet into the sedimentation tank using DPM. The fate of each of these ejected discrete particles is reported at the end of the particle tracking process and also their unique path can be traced in the post-processing. This process of particle tracking is done for each of the particle classes by taking the mean particle size as their representative particle diameter. Finally, the settling efficiency (E_i) for each of the particle classes is calculated using Eq. (4), and then the total settling efficiency (E_{total}) for each of the 6 cases studied is calculated.

A converged solution is deemed to be obtained only when the mass flow rate imbalance between the inlet and outlet is less than 1% and the residuals of each of the variables fall below 10^{-4}. It takes approximately 10 h for these conditions to be fulfilled for a single simulation. All the simulations performed in this study are carried out in a workstation that has 24 cores and 64 GB of memory using the commercial CFD solver—ANSYS Fluent®.

For the particle tracking process, 26,724 discrete particles are injected from the inlet surface with the same velocity magnitude and direction as that of the primary phase. A test similar to the grid-independence test was also performed for the selection of the number of particles to strike a balance between total computational time and the accuracy of the result obtained.

3 Model Validation

The numerical model adopted for this study is validated by comparing the settling efficiencies obtained using our model (for the WWT particle size distribution data) with that of the counterpart experimental values of Vahidifar et al. [7] for identical flow conditions and geometry. As can be seen from Fig. 4, there is a good agreement between the two studies except for the values of some fine particle sizes. The discrepancy of the settling efficiency values in this particle size range may be due to some erroneous readings in the experimental readings of Vahidifar et al. [7] since the settling efficiency of larger particles is always higher than that of the finer particles in nature, which is not the case in the experimental values. The same discrepancy was also observed in their study when they compared the experimental values with results from their numerical simulations in their quest to find a better-suited turbulence model for their study.

4 Results and Discussions

The effectiveness of the longitudinal inclined plates can be investigated by comparing the settling efficiencies in Table 1. Huge improvement in the settling efficiencies is observed—24.87% and 15.60% increase in total settling efficiency for the WWT and PWT particle size distribution, respectively—due to the introduction of the longitudinal inclined plates in the settling region. Besides the total settling efficiency, the settling efficiency for each of the particle classes is higher for the modified tank compared to that of the original tank.

From Fig. 5, it is observed that there is excellent dissipation of the turbulence kinetic energy after the addition of longitudinal inclined plates. This decrease in

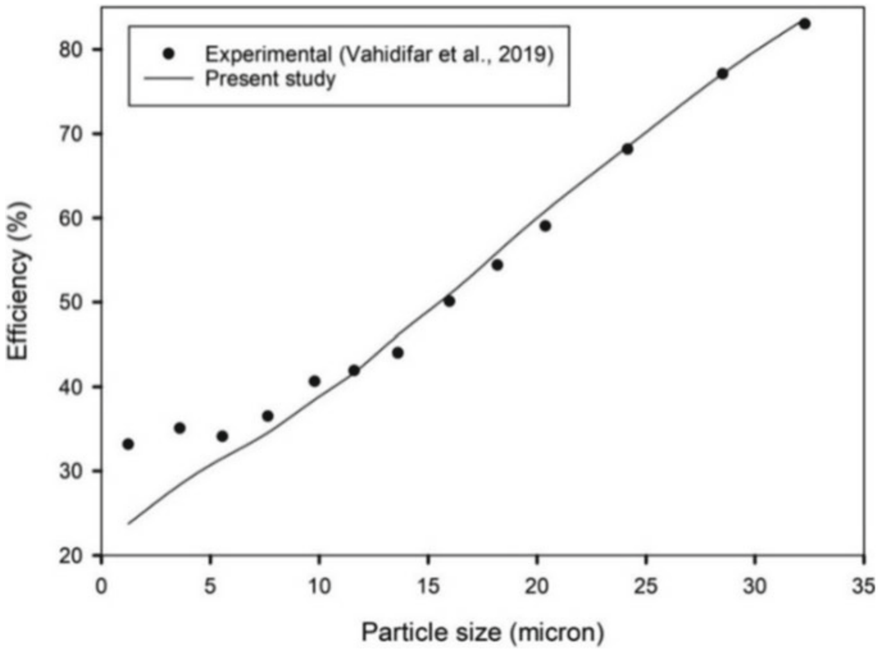

Fig. 4 Comparison plot of settling efficiencies obtained from this study with the counterpart experimental values of Vahidifar et al. [7]

Table 1 Calculated settling efficiencies for each of the particle classes

WWT	Efficiency		PWT	Efficiency	
Particle size (μm)	Original tank	Modified tank	Particle size (μm)	Original tank	Modified tank
1.232	33.16	50.47	20	26.69	50.90
3.6035	35.07	52.38	50	32.56	56.17
5.557	34.10	55.11	80	38.77	64.78
7.643	36.50	58.71	120	48.81	79.84
9.792	40.65	64.05	170	62.24	95.63
11.6045	41.93	68.70	200	69.64	98.96
13.6075	44.00	74.36	250	79.90	99.75
15.9815	50.08	81.64	350	92.17	99.74
18.188	54.39	87.89	450	95.84	99.75
20.385	59.03	93.14	550	96.43	99.88
24.1675	68.15	98.11	650	96.64	100.00
28.5265	77.10	99.42	750	97.30	100.00
32.3	83.01	99.81	850	97.41	100.00
Total efficiency	42.67	67.54	Total efficiency	79.15	94.75

turbulent kinetic energy allows the non-chaotic flow of sediments which results in easier sedimentation. Also, from Fig. 6, it is clear that the re-circulating currents have been eliminated besides slowing down the flow velocity, especially at the bottom part of the tank. This helps in eliminating any chances of re-suspension of settled particles.

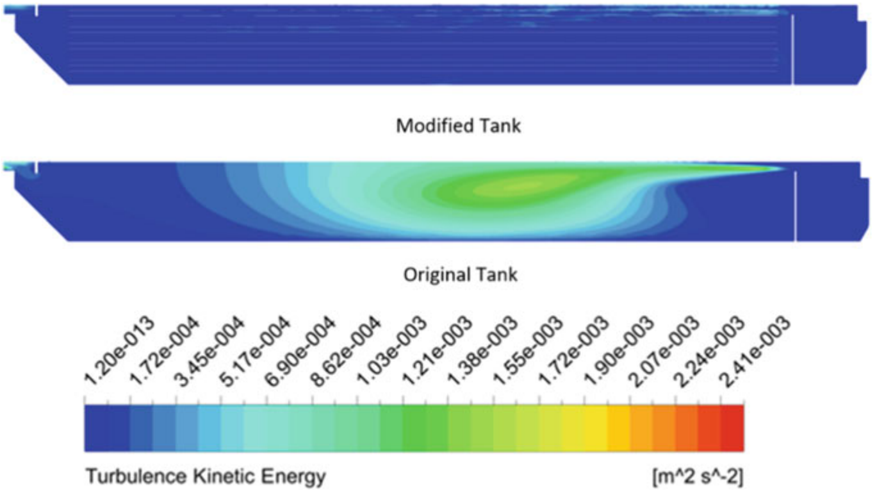

Fig. 5 Comparison of the contour of turbulence kinetic energy at the mid-width plane of one longitudinal half ($x = 2.875$ m)

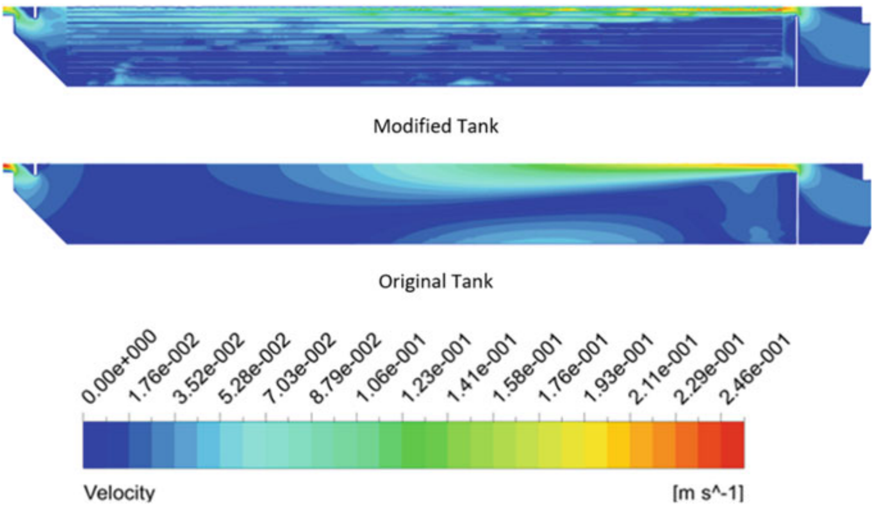

Fig. 6 Comparison of contour of velocity magnitude at mid-width plane of one longitudinal half ($x = 2.875$ m)

From these observations, it can be safely concluded that the longitudinal inclined plates are very much effective in increasing the settling efficiency and also the overall performance of the sedimentation tank by altering the hydrodynamics of the tank to suit the sedimentation process. Moreover, the longitudinal inclined plates also double up as additional settling beds and boost the settling capability of the tank.

5 Conclusion

The effectiveness of the longitudinal inclined plates in increasing the settling efficiency as well as the improvement in the overall performance of a rectangular sedimentation tank is thoroughly investigated through numerical simulations in this study. All the simulations in this study are done using a full-scale 3-D geometry to reduce errors. Experimentally obtained particle size distribution data of both the PWT and WWT are utilised in order to investigate any difference in results due to differences in the properties of the settling particles. The steady flow streamlines are obtained prior to the introduction of the settling particles using DPM and the efficiencies for each of the particle classes are calculated. Modifications are done to the existing sedimentation tank and compared with the original tank for improvements and any negative effects. Below are some of the key conclusions that can be drawn from the results obtained from this study.

- The introduction of longitudinal inclined plates helps in the dissipation of turbulent kinetic energy from the fluid flow and thereby improving the hydrodynamics of the sedimentation tank.
- The velocity of flow within the tank is also reduced greatly which aids in the sedimentation process.
- Adding the longitudinal inclined plates in the settling zone eliminates any chances of forming recirculation currents.

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