Trans. Phenom. Nano Micro Scales, 6(Special): 29-36
DOI: 10.22111/tpnms.2018.23893.1143

ORIGINAL RESEARCH PAPER

Investigating the effect of flow entrance and existence of baffle on sedimentation efficiency using Discrete Phase Model (DPM)

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Received 6 February 2018; revised 17 March 2018; accepted 22 April 2018; available online 6 May 2018

ABSTRACT: Presence of salts in water has been one of the biggest problems of industrial equipment such as evaporators, boilers, and pipes. These salts gradually form scales on evaporators and boilers tubes and reduce their efficiency. Pretreatment processes are conducted to remove these salts; with sedimentation tanks being one of the essential equipment used in these processes. This study numerically simulates multiphase flows in the sedimentation tanks using Discrete Phase Model (DPM). Various important parameters, such as sedimentation tank entrance and existence of baffle in the case of non-homogenous injected particles are studied. The results indicated that the bottom entrance tank provides maximum sedimentation efficiency of 70.3%. In addition, baffle influence is dependent on entrance location; and in the case of the top entrance, baffle presence improves efficiency by 5.2%. Sedimentation tank efficiency is also demonstrated for different particle sizes, indicating a 100% efficiency rate of the sedimentation for particle sizes at 50 microns or higher.

KEYWORDS*: Baffle, Discrete Phase Modeling, Efficiency, Sedimentation, Tank entrance*

INTRODUCTION

Water treatment is an important issue due to water scarcity, compelling it to return back into the usage cycle. Other serious reasons for water treatment are scaling and corrosion prevention in boilers and cooling equipment; therefore, it is necessary to maintain the water quality to the extent permitted by the various treatment processes.

Many researchers analyzed and modelled settling in the second (sedimentation) tank. Larsen [1] used CFD models to analyze sedimentation tanks. Imam et al. [2] carried out their simulation with a constant sedimentation rate assumption, and used mean discrete particle velocity. Lin et al. [3] Simulated in six different sizes of particles, taking into account the velocities associated with them. Kim et al. [4] used the power-law to analyze the flows with SIMPLE method. Owen [5] examined the rate of particle settling velocity. He defined a “relaxation time” parameter, suggesting that small particles that have a relaxation time that is less than the time characteristic of field vortices, follow the flow path. He proposed stokes number which is the ratio of both mentioned time scales to determine whether the particle follows the flow path or not.

Tarpagkou and Pantokratoras [6] studied the effect of Stokes number on particle sedimentation velocity. Their study showed smaller particles (lower stokes) follows the flow path, but larger particles don’t show this characteristic and have a higher tendency to settle. Tarpagkou et al. [7] analyzed the effect of the existence of inclined plates (lamella) on particle sedimentation by the Eulerian-Lagrangian method.

Their results demonstrated that presence of lamella reduces vortices in the tank, creating suitable conditions for sedimentation.

Goula et al. [8] analyzed the circular deposition tank with the eulerian-lagrangian approach, using the DPM model and examined the effect of temperature on the performance of the tank. Guihua Zhu et al. [9] studied the effects of velocity controlling blades (baffle) presence in vertical sedimentation tanks.

They concluded that baffles slow down the flow in vertical tanks. Shahrokhi et al. [10] also studied the effects of baffle position on sedimentation rate.

In their research, it has been claimed that the presence of a baffle, causes the reduction of circulating volume in lower part of tank in comparison to non-baffle mode and baffles prevent large vortices, disrupting the sludge layer created at the bottom of the tank, replacing them with smaller vortices, which are unable to disrupt the sludge layer. In other words, the turbulence flow turns into a laminar flow after the baffles. Asgharzadeh et al. [11] investigated the effect of single and a combination of baffles on the sedimentation and concentration distribution of the tanks.

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Tel.:+982182884918; Note. This manuscript was submitted on *March* 6, 2018; approved on *January* 22 April, 2018; published *May 6,2018.*

	Nomenclature		Greek Symbols
A	area (m^2)	α	volume fraction
C	concentration (kg/m^3)	υ	viscosity (m^2/s)
C_d	Friction factor	μ_{eff}	effective dynamic viscosity (m^2/s)
d	diameter (m)	ρ	density (kg/m3)
g	gravitational acceleration (m/s^2)	$\vec{\lambda}$	unite vector
F	force (N)		**Subscripts**
Fr	Froude number	i	main direction
m	mas (kg)	in	inlet
P	pressure (N/m^2)	out	outlet
Q	fluid flow rate (m^3/s)	fr	friction
u,v	x and y components of velocity (m/s)	g	gravitational
U	mean velocity (m/s)	br	brownian
Re	Reynolds number (m)	b	buoyancy
x,y	Cartesian coordinates (m)	pg	pressure gradient
		ur	relative Velocity

Razmi et al. [12 used the VOF multiphase model to analyze the flow field in the tank in the presence of baffle]. Yaqubi et al. [13] investigated empirically the flow parameters of high turbidity flow in a deposition tank. They calculated the impact of the baffle on the fluid flow and concentration distribution along the tank. Liu et al. [14] studied one-dimensional sedimentation models in sedimentation tanks, comparing different models. Jin et al. [15] studied sedimentation in class(I) sedimentation tanks with non-homogenous particles. Long Fan et al. [16] reviewed the secondary deposition tank with CFD and analysed the velocity profile as well as the distribution of the concentration in the tank, and discussed the height and position of the baffle. Flamant et al. [17] used a laboratory device, examined the velocity profile in the deposition tank, they took into account the effect of the presence of the sludge layer by adding a source term in one-dimensional settling equation.

The purpose of this paper is to study fluid flow in sedimentation tanks in the presence of solid particles and investigating the two effective parameters on efficiency in sedimentation tanks: the first one is Sedimentation tank entrance flow location and the second one is the existence of velocity controlling blades (baffles). Computational Fluid Dynamics (CFD) was used by ANSYS CFD to achieve this goal. Fluid interactions on particles and vice versa were also taken into account.

MATRIALS AND METHODS

Fluid Phase:

The fluid in this research behaves in a continuous, incompressible manner. The fluid phase is simulated by Navier-Stokes equations. The continuity (1) and linear momentum (2) equations are as follows:

$$\nabla.(\rho u) = 0 \tag{1}$$

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

Discrete Phase

Discrete particle movement path is calculated by integrating each particle's momentum equation in Lagrangian reference framework. Equation (3) shows the forces affecting the particles:

$$m_p \frac{du_p}{dt} = F_{fr} + F_g + F_b + F_{br} + F_s + F_{pg} + F_{vm} \tag{3}$$

The vectors on the right side of the equation represent friction, gravitational, buoyancy, brownian, saffman lift, pressure gradient and virtual mass forces, respectively. Among the acknowledged forces, only the brownian and saffman lift forces are negligible. All forces applied to the particle are shown in Table 1.

Fluid-particle interactions:

The most important assumption for simulating multiphase fluids in a sedimentation tank is the interaction between the primary (water) and the secondary (particle) phases. In this paper, a volumetric fraction at 0.2 (kg/m3) entrance concentration is calculated by equation (4):

$$\alpha = \frac{C_p}{\rho_p} \approx 10^{-4} \tag{4}$$

Therefore, two-way interaction should be noted to simulate.

In other words, in addition to the effects of the primary phase on the secondary phase, the effects of the secondary phase on the primary phase should be taken into account as well. This is considered by the discrete phase source term (sdq) in the fluid momentum equation (Eq. (2)).

Table1
Forces applied to particles.

Force	Expression	Note	Ref.
Friction	$F_{fr} = \frac{1}{2} C_d A_f \rho_f \lvert u_r \rvert^2 \vec{\lambda}_{u_r}$ $C_d = \frac{Re_r}{24} [1 + 0.15(Re^{0.687})$	This force is Counted as the most important force in this study.	[18]
Gravitational	$F_g = \frac{\pi \rho_p d_p^3}{6} g$	This force is dependent on Earth's gravitational acceleration and proportional to particle's mass.	[19]
Buoyancy	$F_b = -\frac{\pi \rho_f d_p^3}{6} g$	This force is due to the sum of the difference in fluid pressure around the body; the force acts in the opposite direction of gravity and is proportional to the volume of the body and the density of the carrier fluid.	[20]
Virtual mass	$F_{vm} = \frac{1}{2} \frac{\rho_f}{\rho_p} \frac{d}{dt} (u_f - u_p)$	This force is important when fluid density relative to particle density is higher than 0.1.	[21]
Pressure gradient	$F_{PG} = m_P \frac{\rho_f}{\rho_P} \left(\frac{du_f}{dt} - \nu_f \Delta u_f \right)$	This force is derived from the full Navier-Stokes equation, showing the force induced on a fluid that would occupy the field in the absence of the particles.	[20]

Turbulence:

According to the problem conditions and the geometry in question, **k-Ɛ** turbulence model was chosen to analyze the turbulence. General transport equations for turbulence kinetic energy k, as well as turbulence dissipation rate Ɛ are considered as follows.

$$\frac{\partial}{\partial x_j}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(a_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho \varepsilon \tag{5}$$

$$\frac{\partial}{\partial x_j}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left(a_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon \tag{6}$$

The effects of field turbulence on the particles:

Flow turbulence and fluid velocity fluctuations directly affect particle movement; this way, the fluid momentary velocity felt by the particle changes due to the applied forces. Discrete Random Walk model uses gaussian random dispersion based on natural random events to define the effects of turbulence on the particle.

Boundary conditions:

Velocity-inlet boundary condition is used at sedimentation tank entrance. Pressure-outlet boundary condition is used in the tank outlet.

The free surface of the tank uses symmetry condition. The discrete phase uses the trap boundary condition at the bottom of the tank, and reflection boundary condition on the walls.

Geometry:

The sedimentation tank geometry subject to study has been acquired from [10] and is of rectangular shape. It measures at 50 cm wide, 31 cm height and 200 cm long. The inlet entrance height is 10 cm. The tank overflow is located at 30 cm high.

The baffle height to the depth of the sedimentation tank equates 0.176 ($\frac{H_b}{H} = 0.176$); while its location distance to the tank length equals 0.125 ($\frac{L_{baffle}}{L_{tank}} = 0.125$) [10].

Incoming water volume rate in the experimental work equals 2 liters per second (Qin=2 lit/s).

According to the flow rate and entrance cross-section area, water velocity was set at 0.04 m/s in numerical calculations.

Reynolds dimensionless number was set at Rein=3972 by the inlet, while Froude dimensionless number was fixed at Frin=0.04 by the inlet; kept the same in all the cases [10]. Figure 1 shows a two-dimensional picture of the tank:
x-momentom equation:

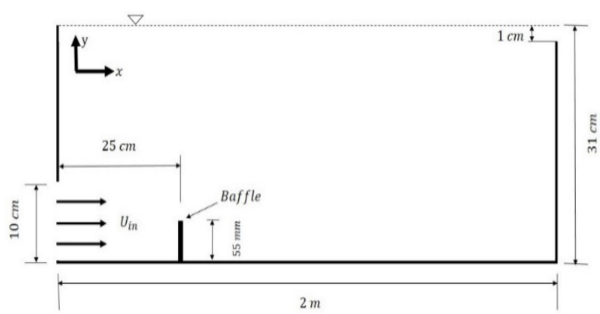

Fig. 1. Sedimentation tank 2D view with the baffle

According to Figure 2, which demonstrates the velocity profile in tank depth, it can be concluded that the two-dimensional approach does not differ significantly from the analysis in the three-dimensional state; while avoiding the extra computational expense required by 3D analysis.

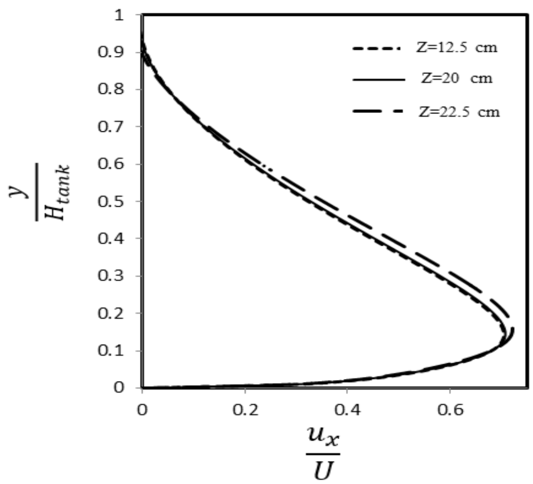

Fig. 2. Investigating velocity profiles in the depth of the tank (At Z= 0.125, 0.2, and 0.25 m deep)

Velocity profile along the tank was compared in three difference mesh sizes to prevent dependence on the number of 2D geometry meshes. Mesh specifications are shown in Table 2:

Table 2

Characteristics of the studied 2D meshes.

Mesh Tittle	Number of Cells
Mesh 1	53440
Mesh 2	83660
Mesh 3	148945

As shown in Figure 3, mesh (2) and mesh (3) have identical velocity in the direction of the tank, so we can consider mesh number 2 as the optimal in a 2D analysis.

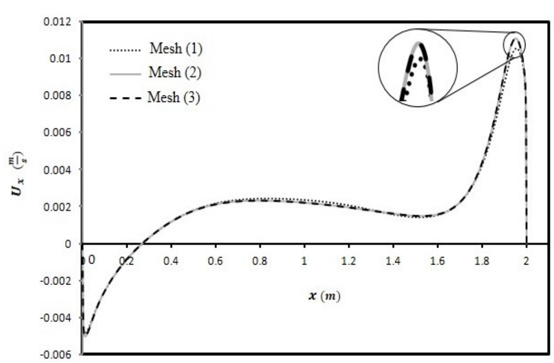

Fig. 3. Investigating velocity profiles in the direction of the tank

VALIDATION

Simulation results were compared with the experimental ones obtained by Shahrokhi et al. in their paper [10] (figure 4). As evident, simulation results are in suitable agreement with experimental results. Primary water phase has a density and viscosity of 998.2 (kg/m3) and 0.001003 (kg/m.s), respectively. The secondary solid phase has a density of 2650 (kg/m3).

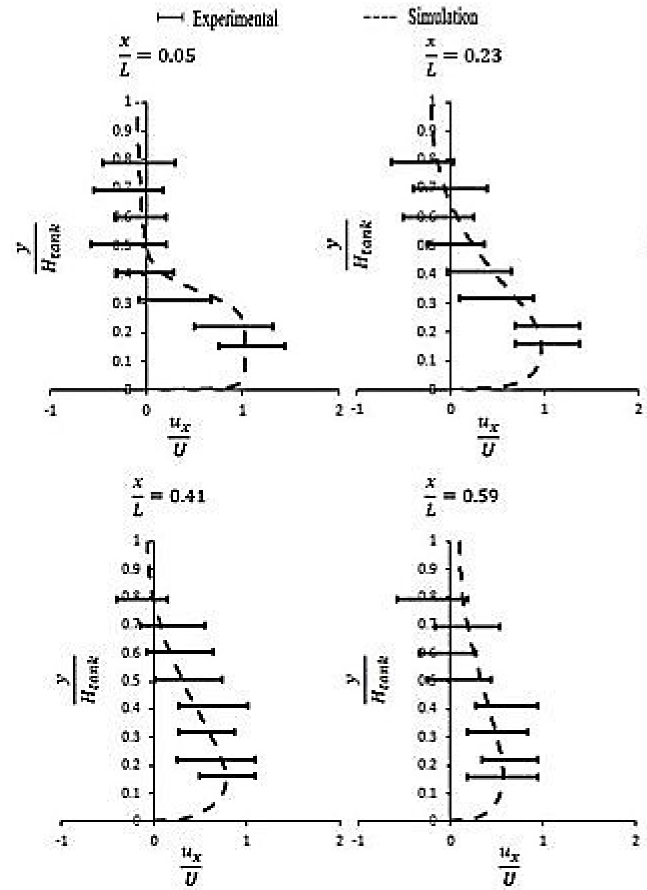

Fig. 4. Comparing velocity profiles with experimental data from [10] along the tank at 0.05, 0.23, 0.41, and 0.59 ratios

Incoming secondary phase concentration was considered as C_{in}=0.2 (kg/m3). Information concerning size distribution of the particles injected into the sedimentation tank is shown in Table 3.

Table 3

Particle mass distribution based on size

Particle Mass Class on Size (PSD)	Particle Diameter (mm)	Inlet Stream Diameter Distribution (%)
1	<0.005	2
2	0.005 □ 0.01	8
3	0.01 □ 0.025	17
4	0.025 □ 0.05	22
5	0.05 □ 0.1	20
6	0.1 □ 0.25	14
7	0.25 □ 0.5	11
8	0.5 □ 1	6

DISCUSSION AND CONCLUSION

In this section, three cases of different inlet positions as well as three cases with baffles, a total of six cases, have been studied; the efficiency of each case was obtained using equation 7:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \tag{7}$$

Figure 5, shows the physics of these three cases without the baffle. It should be noted that in all the three cases, inlet height was considered 10 cm.

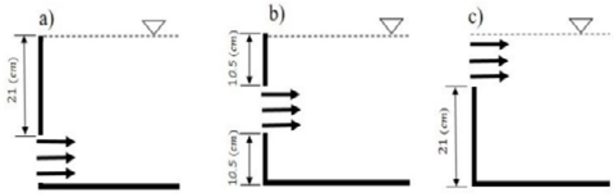

Fig. 5. Geometry of three studied cases without baffle

Figure 6, shows the three cases with baffle. The baffle is located at 25 cm far from the inlet. Shahrokhi et al. stated this distance as most efficient in their work [10].

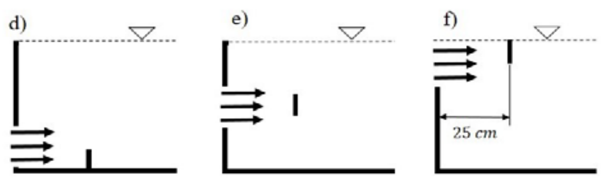

Fig. 6. Geometry of three studied cases with baffle

Fluid flow in the sedimentation tank was investigated in single-phase and two-phase forms (figure 7). This figure depicts that the presence of the secondary phase at 0.2 kg/m3 concentration has little effect on the flow of the primary phase. Stamou et al. stated that in the sedimentation tanks, if the secondary phase concentration is less than 0.2 (kg/m3), then the second phase will not affect the flow field inside the tank [22]. It is worth noting that in the present study, the two-way effect is considered, and the effect of primary and secondary phases on each other has been considered simultaneously.

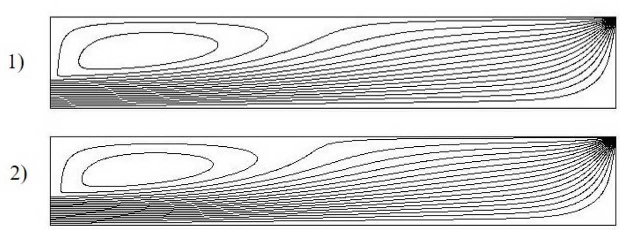

Fig. 7. Studying the flow in two conditions: 1) Single-phase 2)Two-phase

In Figure 8, efficiency in different cases (without baffle) is demonstrated. According to the figure, the highest efficiency occurs in case a (bottom entrance) which is equal to 70.33%. In the middle entrance (case b), and top entrance (case c), the efficiencies are 65.31% and 64.38%, respectively. Hence employing the entrance at the bottom of the tank increases the efficiency by 5.95% compared to the top entrance case. In fact, due to the formation of boundary layers, the velocity closer to the walls is lower compared to positions further from the bottom of the tank, and lower velocities provide better settlement conditions.

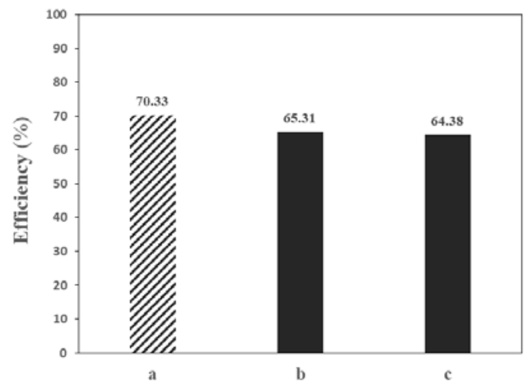

Fig. 8. Efficiency in three different cases in the absence of baffle (cases a, b, and c)

Another reason of increasing efficiency in the case of bottom inlet (case a) is that the primary flow passes through a longer path to exit the tank (tank outlet is located at the top. figure 1) and due to the same flow velocity in all three cases, the tank time scale is increased. This phenomenon leads to the increase in sedimentation tank efficiency. Figure 9, compares flow stream lines in all cases considering no baffles.

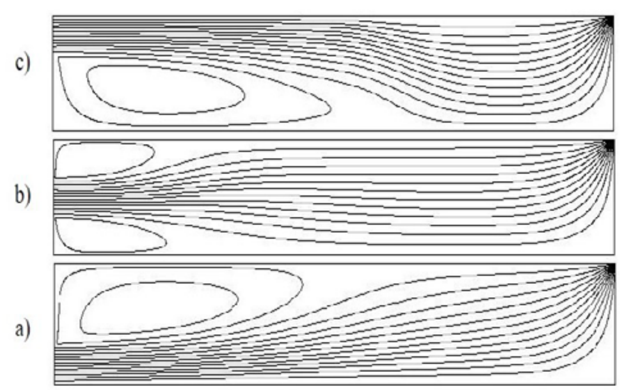

Fig. 9. Studying the flow in the sedimentation tank in cases a, b, and c

Figure 10 shows the efficiency of three cases with different entrance locations considering a baffle. The motivation to embed a baffles is to reduce turbulent kinetic energy and creating laminar conditions for better sedimentation. When baffle is employed in the direction of the flow, case (f) shows the highest efficiency equal to 69.18%. In two other cases d and e, the efficiencies are 66.08% and 65.55%, respectively. The existence of a baffle increases the efficiency of case c by 4.8% and has a positive effect. In contrast, in case a, the baffle has a negative effect and reduces the efficiency by 4.25%. Because the baffle deviates the flow of fluid from the tank floor, which reduces the possibility of particles being deposited. In the middle entrance mode, the baffle increases the efficiency by 0.24%, which is negligible. Because in the middle entrance, the baffle causes about half of the stream to flow from the bottom of the tank and will improve the performance of the tank; In front of the other half, the flow passes through the top of the tank, which reduces the amount of efficiency. Therefore, the two mentioned causes neutralize the effect of each other, and therefore, according to the simulation results, baffle will not have much effect on efficiency.

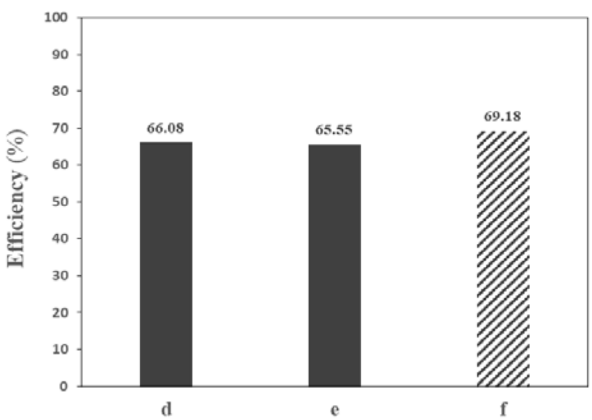

Fig. 10. Efficiency in three different cases with baffle (cases d, e, and f)

In case (f), in addition to reducing turbulent energy, the baffle directs the flow towards the bottom of the tank, improving the condition for sedimentation. In contrast in case (d), baffle causes the particles to move away from the bottom of the tank, requiring more time for proper sedimentation, reducing efficiency as a result (compared to case a, without baffles) (figure 11).

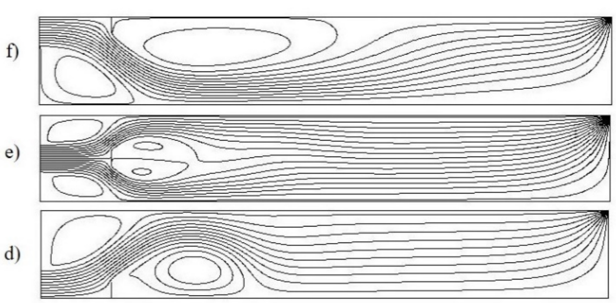

Fig. 11. Studying the flow in the sedimentation tank in cases d, e, and f

The efficiency of the tank is shown in Fig 12 for two cases a (bottom entrance without baffle) and d (bottom entrance with baffle).

According to the figure, the efficiency for classes 5 to 8 is 100%. In other words, in the diameter ranges from 50 to 1000 microns, with baffle and without the baffle, all particles are deposited. Due to the high Stokes number and high gravity, these particles have enough time to settle inside the tank with baffle and without the baffle and despite the changing in the flow field in the presence of baffle, the efficiency of the tank for these particle classes is not changed.

For particles of class 1 (5 microns), in the presence of baffle, the efficiency decreases by 12.57%. Comparing Cases a and d it is obvious that these particles, due to their small size and low Stokes numbers, emigrate from bottom of the tank, thus reducing the efficiency of separation. Particles of classes 2, 3 and 4, obey the same rule and the efficiency for each of these classes is reduced by 11.67%, 15.24% and 16.03, respectively.

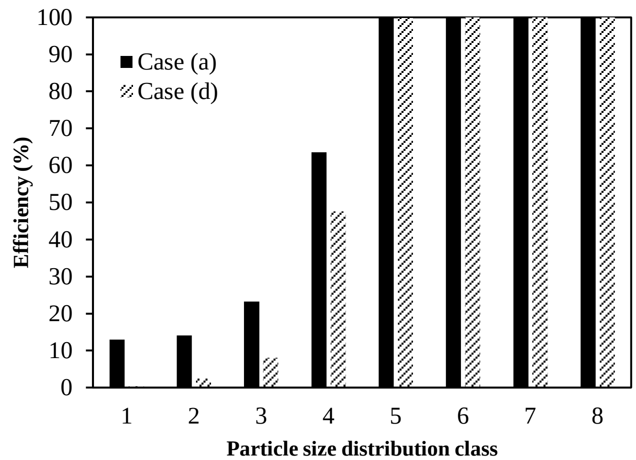

Fig. 12. Particle efficiency in cases a (bottom entrance without baffle) and d (bottom entrance with baffle)

In Figure 13, the efficiency of the sedimentation tank is shown for two cases c (top entrance without baffle) and f (top entrance with baffle). According to the figure for the two cases c and f, the efficiency for the class 6 to 8 particles is 100%.

In case 5, adding a baffle, the efficiency reaches 100%. Also, in classes 1, 2, 3 and 4, the efficiencies have increased by 9.92%, 7.29%, 13.56% and 21.79%, respectively. This increase in the efficiency of different particle classes, due to the deformation of the flow field inside the sedimentation tank, is in the presence of a baffle. The presence of baffles deviates the flow field to the bottom tank and increases the probability of deposition of particles.

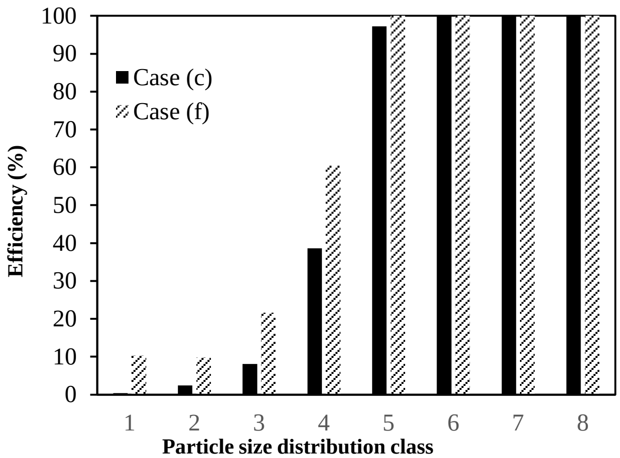

Fig. 13. Particle efficiency in cases c (high entrance without baffle) and f (high entrance with baffle)

Figures 12 and 13 reveal that particle sedimentation in high diameter ranges of classes 5 and higher, is not dependent on entrance position and presence of the baffle. In this range, the main governing mechanism is gravity. In other classes with smaller particles, the effect of gravity decreases, leading to lower sedimentation. This trend reaches a point where the gravity can deem negligible.

CONCLUSION

In the present work a sedimentation tank was analyzed using Discrete Phase Model (DPM). Results indicated that placing the entrance at the bottom provides the highest efficiency due to the specific characteristics of the flow in the tank. In addition, the presence of baffles is affected by tank entrance position, and while the entrance is located at the top, baffles improve sedimentation rates by enhancing fluid flow inside the sedimentation tank and reducing fluid turbulent energy. Particle diameter distribution should also be taken into account to design a sedimentation tank better suited to the task. Finally, results showed that the bottom entrance tank provides maximum sedimentation efficiency of 70.3%. Moreover, in the case of the top entrance, baffle presence improves efficiency by 5.2%. Sedimentation tank efficiency is also demonstrated for different particle sizes, indicating a 100% efficiency rate of the sedimentation for particle sizes at 50 microns or higher.

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