Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2018.22241

111 (2018) 68–78
April

Effect of inlet and outlet baffle position on settling tank performance using experimental investigation and CFD modelling

Emad S. Elmolla[a,b,*], Usama F. Mahmoud[a], Mostafa Hassanien[a]

[a]*Department of Civil Engineering, Faculty of Engineering, Al-Azhar University, Cairo, Egypt, email: dr.usama_fathy@hotmail.com (U.F. Mahmoud), eng_mostafa470@yahoo.com (M. Hassanien)*
[b]*Environmental Engineering Programme, Zewail City of Sceince and Technology, 6th of October, Egypt, email: emadelmolla@gamil.com, eelmolla@zewailcity.edu.eg (E.S. Elmolla)*

Received 8 September 2017; Accepted 19 March 2018

ABSTRACT

Settling is an important unit operation in water and wastewater treatment plants. The objective of this work is to study the effect of inlet and outlet baffle positions (longitudinal and vertical) on the hydraulic characteristics of the settling tank using flow through curve method (FTC). The hydraulic performance of the settling tank was also modelled using computational fluid dynamics (CFD). The use of inlet baffle at the optimum position is significantly improved the settling tank performance in terms actual residence time and presence of dead zones. The optimum inlet baffle position is 5% of the tank length (L) from the inlet and 67% of tank depth upward from the bottom. The use of outlet baffle at the optimum position also improved the settling tank hydraulic performance. The optimum position of the outlet baffle is at 15% L from the outlet and 16% of tank depth upward from the bottom. Effect of inlet and outlet baffle positions on the velocity and kinetic energy were studied using CFD modelling. Significant reduction in dissipation of kinetic energy and reduction of velocity magnitude at the tank inlet due to the use of inlet baffle are proved by CFD modelling.

Keywords: CFD; Inlet baffle; Outlet baffle; Settling tank

1. Introduction

Settling is an important unit operation in water and wastewater treatment plant [1]. It is a physical treatment that utilizes gravity to separate suspended solids from water [1]. Rectangular, circular and square are three geometric shapes commonly used for sedimentation basins in water treatment [2]. Design of settling tanks is mostly based on retention time, uniform flow and uniform vertical velocity of particles [3]. These assumptions are neglecting hydrodynamic phenomena that could occur in the settling tanks and affect the settling efficiency [3]. Problems that may affect the settling tank performance include density current, dead zone, strong surface current, recirculating current, short circuiting, channelling and inefficient sludge removal [4].

When water enters a sedimentation tank, water may not move uniformly from the inlet to the outlet [5]. Most of water could mix into the main body of the basin and then slowly leave the tank in a reasonable period; however, some water will enter and leave the tank in a short period of time [5,6]. This is called hydraulic 'short-circuiting' because it has short-circuited the full treatment process. Some of the water might enter a hydraulic dead zone and remain there for some time [6,7]. The short-circuiting could be caused due to direct channelling from the inlet to the outlet, wind effects, thermal stratification [4,6]. Dead zones are defined as circulation zones in settling tanks and it occupies a considerable volume of the tank, which could decrease the effective volume of settling process [8]. Circulation region or dead zone creates high flow mixing problems in the settling tanks [9]. Thus, decreasing the formation of the dead zones is an important objective of the settling tank design [9]. Suitable baffle configuration is reported to be a suitable methodology for dead zone reduction and influent energy dissipation [10]. Baffle configuration has been studied by many researchers as reported in the literature. However, flow through curves (FTC) was the

*Corresponding author.

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widely applied method for evaluating the effect of baffle configuration on the settling hank hydraulic characteristics [11–14]. Hydraulic efficiency of the sedimentation tank could be evaluated using different parameters obtained from FTC analysis. The T_{max} is the time when the maximum concentration at the outlet was achieved. The higher T_{max}/T_{TH} values the better hydraulic characteristics and vice versa. The t_{10} value is one of these parameters that could be used to predict a short-circuiting in the sedimentation tanks. The t_{10} is the time which 10% of the tracer volume that was added to the system exits. Higher t_{10} value represents the less possibility of short circuiting and vice versa [11–14,18]. The maximum value of t_{10} is 1.0 and it is achieved at ideal plug flow; however, the minimum value of zero is achieved at complete mixing [45]. The $t_{50,}$ is time to exit 50% of the tracer volume tracer that was added to the system. The $t_{90,}$ is time to exit 90% of the tracer volume tracer that was added to the system. The parameter of t_{90}/t_{10} is used to predict the degree of mixing. Higher value of t_{90}/t_{10} represents the highly mixed flow [11–14,18]. Value of t_{90}/t_{10} is 1.0 for ideal plug flow and 21.9 for complete mixing [45].

Razmi et al. [8] investigated the effects the baffle position by experimental and numerical approaches. They concluded that the presence of inlet baffle significantly reduced the dead zones size and turbulent kinetic energy. Wills et al. [15] reported that the performance of by using baffles. Results showed that the performance of full scale sedimentation tank increased when transverse baffles are used. Tamayol et al. [16,17] studied the effect of a simple baffle at different positions. They concluded that when the baffle is located at improper position or it has improper height, the performance of primary sedimentation tank would be decreased. Adams and Rodi [18] found that smaller inlet causes less removal efficiency because high velocity due to small inlet may cause recirculation zone. Ahmed [19] studied the effects of inlet baffle position with different contractions on the flow pattern in secondary sedimentation tank. He reported that the best inlet baffle position at 5% of the tank length from the inlet and contraction at 67% of the tank depth from the bottom.

Computational fluid dynamics (CFD) calculations have been employed to improve the process design [20]. Water flow patterns inside sedimentation tanks may be predicted by solving the partial differential equations using CFD [21]. Applications of CFD modelling for the simulation of the water and wastewater sedimentation tank s have been reported in the literature [22–32]. Razmi et al. [8] used the CFD for verification of the experimental data for optimum baffle location. They concluded that presence of baffle can reduce the turbulent kinetic energy. Shahrokhi et al. [33] studied the effect of baffle location on the flow pattern in a rectangular primary sedimentation tank using experimental work and CFD modelling. The results showed that CFD modelling output agreed with experimental results. Goula et al. [21] studied the use of CFD modelling to evaluate the effect of vertical baffle addition in a full-scale sedimentation tank. They reported that vertical baffle addition decreased the dead zone and enhanced the settling of solids by directing them towards the bottom of the tank. The settling efficiency increased from 90.4% (no-baffle) to 98.6% after baffle addition. Sajjadi et al. [34] applied computational fluid dynamics simulations with FLUENT software to assess the effect of height and position of baffle in irrigation settling basin. Abbas et al. [35] used computational fluid dynamic model to study the performance improvement of water treatment plants. The results showed that the use of baffle force the solids to move faster towards the tank bottom and decrease the inlet recirculation zone. The overall solids removal efficiency increased from 50 to 90.5% after baffle addition.

The objective of this work is to investigate the effect of inlet and outlet baffle positions (longitudinal and vertical) on the hydraulic characteristics of the settling tank using flow through curve method (FTC). Effect of inlet and outlet baffle positions on the velocity and kinetic energy were modelled using computational fluid dynamics (CFD).

2. Materials and methods

2.1. Experimental design and procedures

The experiments were conducted using a pilot scale rectangular sedimentation tank. The tank and baffles were made from transparent material (Plexiglas). The tank sizing was 150 cm length, 60 cm width and total depth of 40 cm. However, water depth was 30 cm. Fig. 1 shows a photo of the sedimentation tank and the baffles. However, Fig. 2 shows schematic for the system. Provision for different baffle positions was considered during the pilot fabrication.

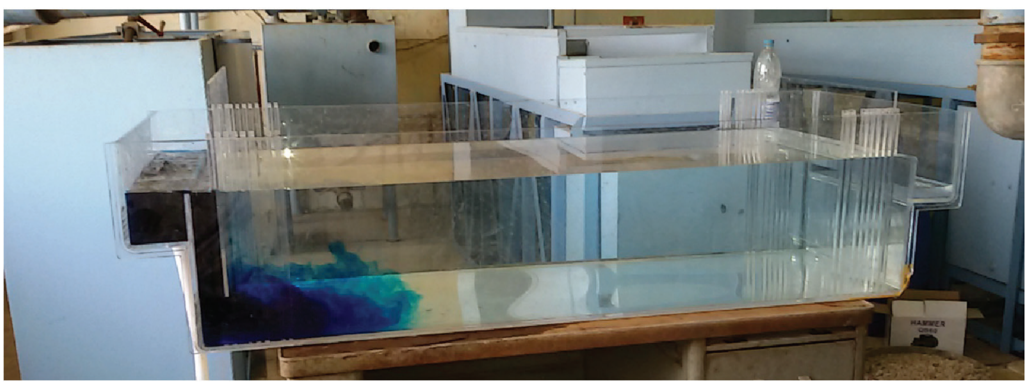

Fig. 1. Photo of the pilot scale sedimentation tank.

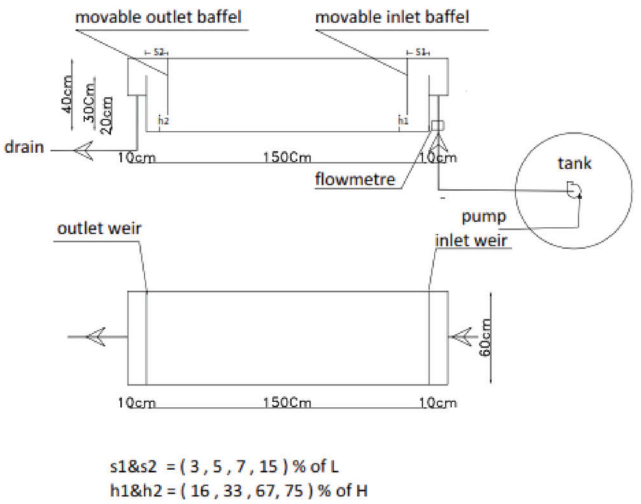

Fig. 2. Schematic diagram for pilot-scale sedimentation tank.

The considered inlet and outlet baffle longitudinal positions were 3, 5, 7 and 15% of the tank length. However, the considered inlet and outlet baffle vertical positions were 16, 33, 67 and 75% vertical bottom contraction of tank depth. The baffle plate was adjusted vertically at the required position by means of stopper. A stainless steel tank with capacity of 1 m^3 is used to store the raw water. The pilot is equipped with feed submersible pump located in the raw water tank. A tap water was used as a raw water source. The flow rate throughout the experimental work was 0.25 l/s and submersible pump was used to supply the required flow. The pilot dimension, operating condition and hydraulic parameters are comparable with that reported in the literature as summarized in Table 1.

Dye tracer method was used to simulate the actual flow conditions [1]. A slug-dose testing method was used in this study; 500 ml of Methylene blue is injected before the inlet weir of the sedimentation tank. The duration of tracer injection is kept less than 2% of the theoretical detention time of the tank at recommended in the literature [1]. The theoretical detention time (T_{TH}) of the settling tank is equal V/Q, where Q is the flow rate in the tank and V is the volume of the tank. However, T is the time when the sample was collected. T_{max} is the time when the maximum concentration at the outlet was achieved. The high T/T_{TH} means better hydraulic characteristics and vice versa. In this case actual retention time is close to the theatrical time. After the dye injection, samples are collected at the tank outlet every 2 min for 18 min. The selection of 2 min interval was due to sampling processing requirements. Spectrophotometer is used to measure the colour concentration. Colour concentration was converted to dye concentration by means of calibration graph presented in Fig. 3.

As reported in the literature by Tamayol et al. [3], design of settling tanks is based on detention time T of particles and flow in the settling tank. Hydraulic efficiency of the settling tanks is also related to detention time of the tank. If detention time is greater than the time that is needed for particles to reach the tank bottom then the particles would settle, otherwise particles may exit the tank with the effluent [3]. For the determination of the performance of a tank, flow through curves (FTCs) is used [39]. FTC gives some good information about mixing and short-circuiting degrees of the tank. In FTC, dye is injected in the inlet for a time of about 10% of t_{TH} then the dye concentration is measured at the tank outlet and plotted versus time [39]. For a better comparison, the concentration is normalized by C_0 which is the mean concentration of the dye injection in the tank (C/C_0). C_0 is calculated by dividing the total mass of injected dye by the volume of the tank. Time axis is normalized by

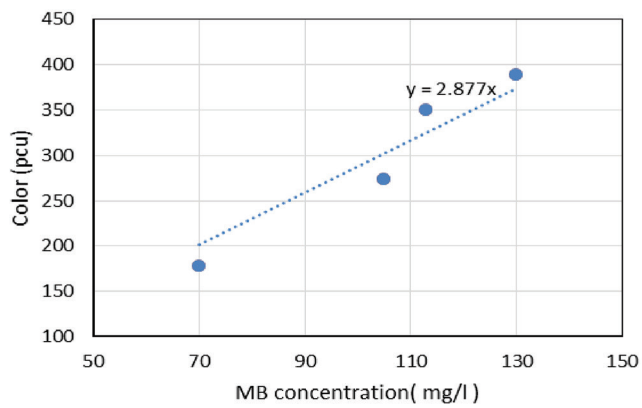

Fig. 3. Relation between colour concentration and Methylene blue concentration.

Table 1
Dimensions and hydraulic parameters for previous and this study

Authors	L (m)	W (m)	h (m)	Q (m^3/s)	$T^{(1)}$ (min)	v_h $^{(2)}$ (m/s)	R_h $^{(3)}$ (m)	$Re^{(4)}$	$Fr^{(5)}$
Takamatsu and Naito [36]	0.4	0.1	0.18	2×10^{-5} to 8×10^{-5}	1 to 1.5	1.11×10^{-3} to 4.44×10^{-3}	0.0869	33.26 to 133.06	3.21×10^{-6} to 5.14×10^{-5}
Stovin and Saul [37]	2	0.972	0.196	1.59×10^{-2}	4	8.35×10^{-3}	0.1396	1.452×10^{4}	0.0134
Taebi-Harandy and Schroeder [38]	2	0.5	0.3	2×10^{-4}	25	1.33×10^{-3}	0.136	139.11	1.33×10^{-6}
Ahmed [19]	1	0.4	0.2	1.66×10^{-5}	80	0.21×10^{-3}	0.1	15.87	0.43×10^{-6}
This work	1.5	0.6	0.3	2.5×10^{-4}	18	0.00139	0.15	159.39	1.3×10^{-6}

(1) T_{TH} – theoretical residence time, min = V/Q; v_h – Horizontal velocity, m/s = $Q/w\ h$; Rh – Hydraulic radius, $m = A_w/P_w$, A_w – Cross section area m^2, P_w – wetted parameter m; (4) Re Reynolds number, dimensionless = $(v_h \times R_h)/v$, v – kinematic viscosity = 1.307×10^{-6} m^2/s; (5) Fr – Froude number, dimensionless = $v_h/(g \times R_h)/v$, g – acceleration due to gravity = 9.81 m/s^2.

T_{TH} (T/T_{th}) [3,39]. For the analysis of performance, time when the concentration at the outlet is maximum T_{max} is used.

2.2. Modelling

In this study the FLUENT computational fluid dynamics (CFD) software was used to model the hydraulic characteristics of settling tank under the different phases of inlet and outlet baffle position. Standard *k*-epsilon model was used to solve the model. The *k*–ε model is one of the turbulent models that contain two equations. These two equations are the turbulence kinetic energy equation *k* and the dissipation equation ε. The exact *k*–ε equations contain many unknown and unmeasurable terms. For more practical approach, the standard *k*–ε turbulence model was used [29,40]. The boundary condition for the inlet is the constant velocity. The outlet is indicated as outflow boundary condition. The free surfaces is described as symmetry boundary condition.

3. Results and discussion

3.1. Effect of inlet baffle position

The main purpose of the inlet baffle is achieving uniform distribution of the flow across the width of the settling basin and dissipating incoming velocity [1]. A solid movable baffle was used to separate the inlet compartment from the settling basin. 17 different longitudinal and vertical positions were studied for the inlet baffle. The longitudinal positions of the inlet baffle (s1) that measured from the inlet were 3%, 5%, 7% and 15% of the tank length (L). The vertical positions of the inlet baffle (h1) that measured the opening from the tank bottom to the lower edge of the baffle were 16%, 33%, 65% and 75% of tank depth. Table 2 summarizes the studied cases for the inlet baffle positions.

Table 2
Studied cases for the inlet baffle positions

Case number	Inlet baffle longitudinal position (s1) as a percentage of tank length (measured from the inlet)	Inlet baffle position (h1) as a percentage of tank depth upward from the bottom
1	No-baffle	No-baffle (100%)
2	3%	16%
3	3%	33%
4	3%	67%
5	3%	75%
6	5%	16%
7	5%	33%
8	5%	67%
9	5%	75%
10	7%	16%
11	7%	33%
12	7%	67%
13	7%	75%
14	15%	16%
15	15%	33%
16	15%	67%
17	15%	75%

The effect of varying the h1 in the range of 16%, 33%, 65%, 75% and 100% (without baffle) at s1 of 3% (Cases 1–5) on the settling tank hydraulic characteristics was studied. Fig. 4, shows photos of dye evolution during the experimental works at no-baffle case (Case 1) and with baffle located at h1: 33% and s1: 3% (Case 2). The photos are taken after approximately 120 s of the dye injection. The formation of dead zones are clearly apparent in the left photo in which no baffle was used. Fig. 5 shows peak concentration ratios (C/C_0) at their corresponding residence time ratios (T/T_{th}). The (C/C_0) were 2.54, 2.21, 2.10, 2.75 and 1.59 at h1 of 16%, 33%, 65%, 75% and no-baffle, respectively. The corresponding residence time ratios (T/T_{th}) were 0.23, 0.34, 0.11, 0.23 and 0.22. Table 3 shows the hydraulic parameters of Cases 1–17. As shown in Table 3, Case 3 (3, 33%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 1–5. The higher value of t_{10}/T represents lower short-circuiting conditions. However, lower t_{90}/t_{10} represent lower flow mixing degree. Higher values of t_{50} and t_{max} of this case represent the higher hydraulic efficiency at this position [3]. For the inlet no-baffle case, lower time of peak concentration (T/T_{th}) is achieved. This is could be ascribed to the presence of dead zones and preferential flow paths [41]. The T/T_{th} values increased with the increase of the h1 in the range of 16% to 33%. Then it decreased when the h1 increased further. This could be ascribed to the minimization of dead zones, enhanced flow pattern through the settling tank due to the relation between the baffle longitudinal and vertical positions [3,39,41]. Based on that, the best vertical position (h1) of inlet baffle at longitudinal position of 3% L is 33% of tank depth upward from the bottom.

The inlet baffle position was shifted toward the outlet and s1 was increased from 3% to 5% at h1 of 16%, 33%, 67% and 75% (Cases 6–9). Fig. 6 shows flow through curves (FTCs) of Cases 6–9. As shown in the figure, peak concentration ratios (C/C_0) were 2.17, 2.02, 1.83 and 2.07 at contraction of 16%, 33%, 65% and 75%, respectively. The corresponding residence time ratios (T/T_{th}) were 0.23, 0.23, 0.46 and 0.35. As shown in Table 3, Case 8 (5, 67%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 6–9. The higher value of t_{10}/T represents lower short-circuiting conditions. However, lower t_{90}/t_{10} represents lower flow mixing degree. Higher values of t_{50} and t_{max} of this case represent the higher hydraulic efficiency at this position. Based on the best vertical position of inlet baffle at longitudinal position of 5% L is 65% of tank depth (measured from the bottom). In comparison with Cases 1–5, it is noted that the best inlet baffle vertical position is depending on the longitudinal position of the baffle. The inlet baffle position was 33% of tank depth from the bottom when the baffle is located at 3% of the tank length. However, it was 67% of tank depth upward from the bottom when the baffle is located at 5% of the tank length. This could be ascribed to the preferential flow paths for the flow that could be developed due to changing of the longitudinal and vertical baffle position.

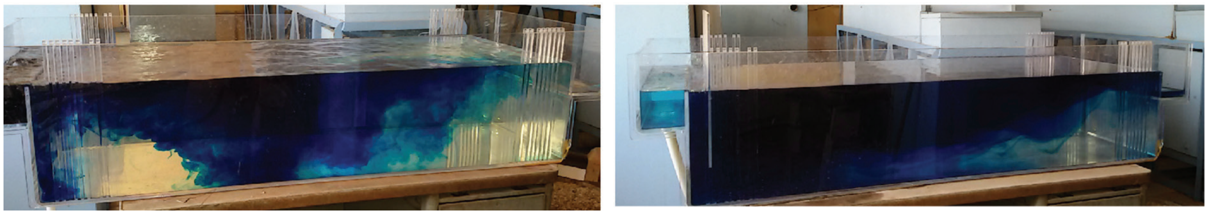

Fig. 4. Photos of dye evolution in without inlet baffle case (left) and with inlet baffle located at h1: 33% and s1: 3% (right).

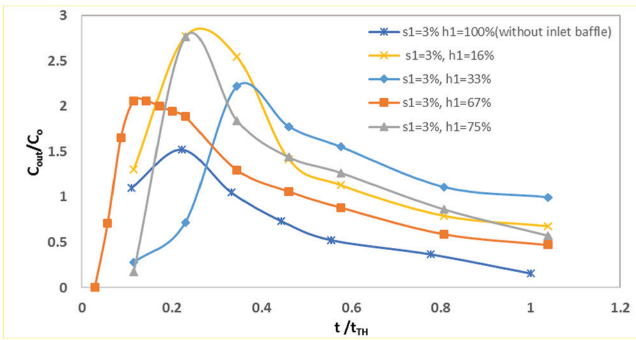

Fig. 5. Time of maximum concentration for different inlet baffle vertical positions (h1 = 16%, 33%, 67%, 75%, without baffle; and s1=3% of the length).

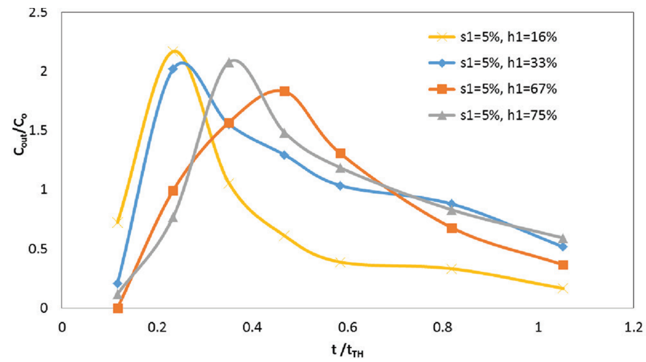

Fig. 6. Time of maximum concentration for different inlet baffle vertical position (h1 = 16%, 33%, 65%, 75%; s1 = 5% of the length).

This interpretation could be supported by the dye evolution photos (Fig. 7). As shown in the figure, the dye plume tends to rise to the surface for the case that baffle is located at h1: 33% and s1: 3% (left photo). However, it takes place mainly between the bottom and middle levels the case that baffle is located at h1: 67% and s1: 5% (right photo).

Table 3
Hydraulic parameters from RTD curve for Cases (1–17)

Cases	s1	h1	t_{10}/T	t_{90}/t_{10}	T_{max}/T	t_{50}/T
1	No-baffle	No-baffle (100%)	0.056	10	0.22	0.228
2	3%	16%	0.092	7.188	0.23	0.346
3	3%	33%	0.216	3.867	0.34	0.404
4	3%	67%	0.069	8.75	0.11	0.167
5	3%	75%	0.144	5	0.23	0.317
6	5%	16%	0.094	5.938	0.23	0.246
7	5%	33%	0.152	4.904	0.23	0.351
8	5%	67%	0.216	3.108	0.46	0.404
9	5%	75%	0.211	3.75	0.35	0.386
10	7%	16%	0.149	5.3	0.23	0.364
11	7%	33%	0.179	4.6	0.35	0.403
12	7%	67%	0.182	4.59	0.35	0.418
13	7%	75%	0.161	5.074	0.23	0.394
14	15%	16%	0.163	5.64	0.26	0.425
15	15%	33%	0.157	5.75	0.26	0.412
16	15%	67%	0.137	6.429	0.39	0.376
17	15%	75%	0.212	4.215	0.39	0.458

Fig. 8 shows the residence time distribution curves when s1 was increased from 5% to 7% at h1 of 16%, 33%, 65% and 75% (Cases 10–13). Peak concentration ratios (C/C_0) were 2.54, 2.18, 1.39 and 1.22 at contraction of 16%, 33%, 65% and 75%, respectively. The corresponding residence time ratios (T/T_{th}) were 0.23, 0.35, 0.35 and 0.23. The interpretation is similar to that described for cases 6–9. As shown in Table 3, Case 12 (7, 67%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 10–13. The higher value of t_{10}/T represents lower short-circuiting conditions. However, lower t_{90}/t_{10} represent lower flow mixing degree. Higher values of t_{50} and t_{max} of this case represent the higher hydraulic efficiency at this position [3]. Based on that, the best vertical position (h1) of inlet baffle at longitudinal position of 7% L is 67% of tank depth.

As in Fig. 9, longitudinal positions of the inlet baffle (s1) were increased further to be 15% (Cases 14–17) with bottom contraction (h1) similar to that of previous cases (16%, 33%, 65% and 75%). Peak concentration ratios (C/C_0) were 1.82, 1.89, 2.53 and 1.93 at contraction of 16%, 33%, 65% and 75% respectively. The corresponding residence time ratios (T/T_{th}) were 0.26, 0.26, 0.39 and 0.39. As shown in Table 3, Case 17 (15, 75%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 14–17. The higher value of t_{10}/T represents lower short-circuiting conditions. However, lower t_{90}/t_{10} represent lower flow mixing degree. Higher values of t_{50} and t_{max} of this case represent the higher hydraulic efficiency at this position. Based on that, the best vertical position (h1) of inlet baffle at longitudinal position of 15% L is 75% of the tank depth.

The inlet baffle best longitudinal and vertical positions determined from the previous cases are compared together

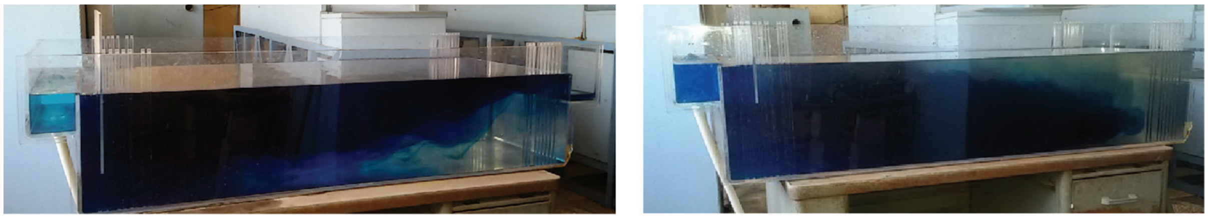

Fig. 7. Photo of dye evolution for the cases that baffle is located at h1: 33% and s1: 3% (left photo) and h1: 67% and s1: 5% (right photo).

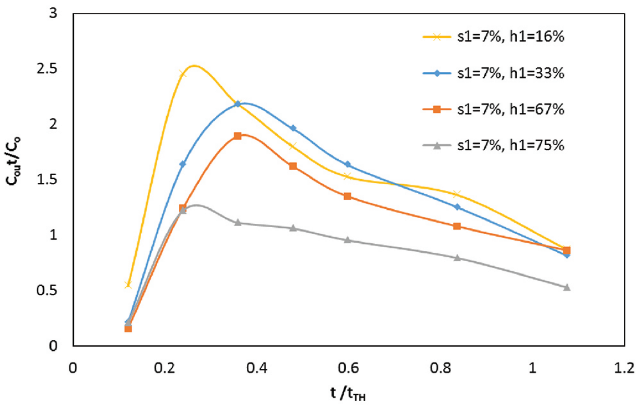

Fig. 8. Time of maximum concentration for different inlet baffle vertical positions (h1 = 16%, 33%, 65%, 75%; and s1= 7% of the length).

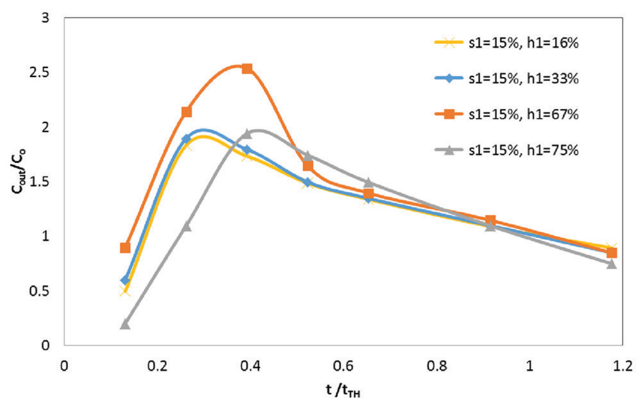

Fig. 9. Time of maximum concentration for different inlet baffle vertical positions (h1 = 16%, 33%, 65%, 75%; and s1= 15% of the length).

as presented in Fig. 10. In all the cases, times of peak concentration (T) are considerably lower than theoretical residence times (T_{th}). This could be ascribed to the presence of dead zones and preferential flow paths [41]. In addition the T/T_{th} of less than 1.0 points to a great deviation from the ideal plug flow behaviour [41]. From the figure, the case with inlet baffle is located at 5% of the length and 67% of tank depth upward from the tank bottom appeared to be the optimum inlet baffle position. This agrees well with that reported in the literature [19]. Table 4 showed the hydraulic parameters of Cases 3, 8, 12 and 17. As shown in the table, Case 8 (5, 67%) has higher values of t_{10}/T and lower value of

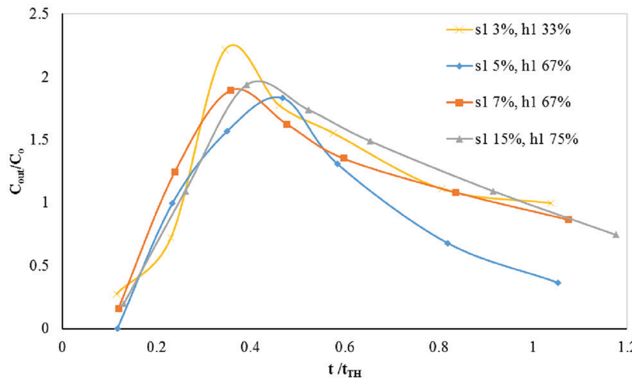

Fig. 10. Comparison between different inlet baffle best longitudinal and vertical positions.

Table 4
Hydraulic parameters from RTD curve for different inlet baffle best longitudinal and vertical positions

Cases	t_{10}/T	t_{90}/t_{10}	T_{max}/T	t_{50}/T
3	0.216	3.867	0.34	0.404
8	0.216	3.108	0.46	0.404
12	0.182	4.590	0.35	0.418
17	0.212	4.215	0.39	0.458

t_{90}/t_{10} which mean lower short-circuiting and lower mixing conditions of the flow occurred at this position. Values of t_{90}/t_{10}, show that degrees of flow mixing is lower than in other cases.

3.2. Effect of outlet baffle position

The effluent structure has a great effect on the flow pattern and settling behaviour of solids in a sedimentation basin [1]. A solid movable baffle was used to separate the outlet compartment from the settling basin. Different outlet baffle longitudinal and vertical positions were studied with total 16 cases. The longitudinal positions of the outlet baffle (s2) were varied to be 3%, 5%, 7% and 15% of the length. However, the vertical positions of the outlet baffle (h2) that measured the opening from the tank bottom to the lower edge of the baffle were varied to be 16%, 33%, 65% and 75% of the height. The experiments were conducted in the presence of inlet baffle located at the optimum position (s1 = 5% and h1 67%) achieved from Cases 1–17. Table 5, summarizes the studied cases for the outlet baffle positions.

Table 5
Studied cases for the outlet baffle position (presence of inlet baffle at h1:67% and s1: 5%)

Case number	Outlet baffle longitudinal position (s2) as a percentage of tank length (measured from the inlet)	Outlet baffle position (h2) as a percentage of tank depth upward from the bottom
18	3%	16%
19	3%	33%
20	3%	67%
21	3%	75%
22	5%	16%
23	5%	33%
24	5%	67%
25	5%	75%
26	7%	16%
27	7%	33%
28	7%	67%
29	7%	75%
30	15%	16%
31	15%	33%
32	15%	67%
33	15%	75%

Fig. 11 shows the effect of varying the bottom contraction of the outlet baffle (h2) in the range of 16%, 33%, 65% and 75% at s2 of 3% (Cases 18–21) in the presence of inlet baffle located at h1: 67% and s1: 5%. As shown in the figure, peak concentration ratios (C/C_0) were 2.80, 1.87, 2.33 and 1.99 at h2 of 16%, 33%, 65% and 75%, respectively. The corresponding residence time ratios (T/T_{th}) were 0.24, 0.36, 0.24 and 0.24. The T/T_{th} values increase with the increase of the vertical contraction in the range of 16% to 33%. Then it deceased when the vertical opening increased further. This could be ascribed to the minimization of dead zones and enhanced flow pattern through the settling tank [3,39,41]. Table 6 shows the hydraulic parameters of Cases 18–33. As shown

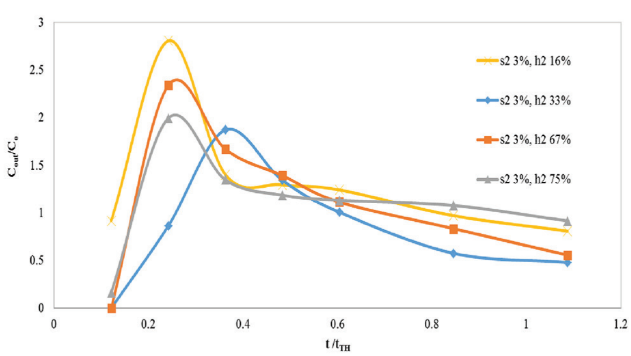

Fig. 11. Time of maximum concentration for different outlet baffle vertical locations (h2 = 16%, 33%, 65% and75; and s2 = 3% of the length).

Table 6
Hydraulic parameters from RTD curve for cases 18–33

Cases	s2	h2	t_{10}/T	t_{90}/t_{10}	T_{max}/T	t_{50}/T
18	3%	16%	0.121	6.75	0.24	0.326
19	3%	33%	0.205	3.882	0.36	0.393
20	3%	67%	0.163	4.852	0.24	0.356
21	3%	75%	0.163	5.37	0.24	0.399
22	5%	16%	0.16	4.808	0.24	0.333
23	5%	33%	0.185	4.790	0.37	0.401
24	5%	67%	0.16	5.462	0.24	0.5
25	5%	75%	0.086	10.071	0.24	0.383
26	7%	16%	0.164	5.423	0.5	0.448
27	7%	33%	0.164	5.192	0.37	0.398
28	7%	67%	0.183	4.862	0.37	0.417
29	7%	75%	0.095	9.4	0.25	0.363
30	15%	16%	0.219	4.603	0.55	0.521
31	15%	33%	0.201	4.81	0.41	0.472
32	15%	67%	0.208	4.167	0.41	0.389
33	15%	75%	0.132	7.421	0.25	0.451

in Table 6, Case 19 (3, 33%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 18–21. The higher value of t_{10}/T represents lower short-circuiting conditions. However, lower t_{90}/t_{10} represents lower flow mixing degree. Higher values of t_{50} and t_{max} of this case represent the higher hydraulic efficiency at this position. Based on that, the best vertical position (contraction) of outlet baffle at longitudinal position of 3% L is 33% of the depth (Case 19).

The outlet baffle position was shift toward the inlet and s2 was increased from 3% to 5% at h2 of 16%, 33%, 65% and 75% (Cases 22–25). Fig. 12 shows flow through curves (FTCs) of these cases. As shown in the figure, peak concentration ratios (C/C_0) were 2.57, 2.53, 2.68 and 2.79 at bottom contraction of 16%, 33%, 65% and 75% respectively. The corresponding residence time ratios (T/T_{th}) were 0.24, 0.37, 0.24 and 0.24. The interpretation is similar to that

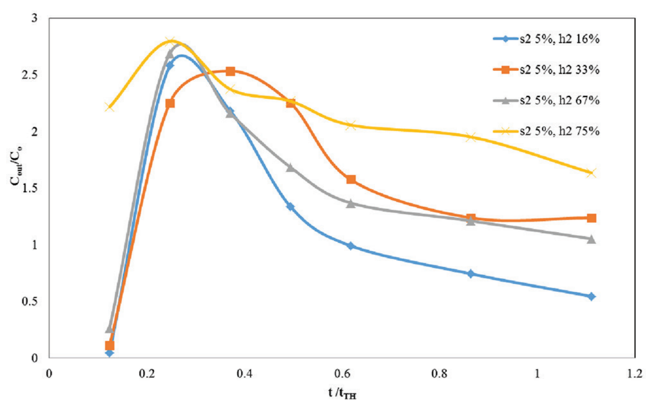

Fig. 12. Time of maximum concentration for different outlet baffle vertical position (h2 = 16%, 33%, 65% and 75; and s2 = **5%** of the length).

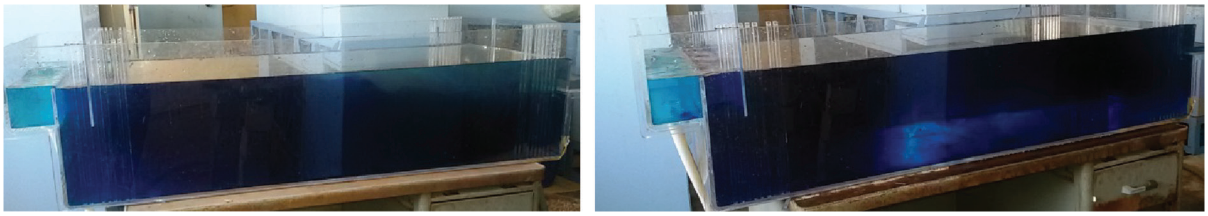

Fig. 13. Photo of dye evolution in Case 8 (left) and Case 23 (right).

described for previous cases. As shown in Table 6, Case 23 (5, 33%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 22–25. The higher value of t_{10}/T represents lower short-circuiting conditions. Based on that, best vertical position of outlet baffle (h2) at longitudinal position of 5% L is 33% of the tank depth (Case 23).

Comparing the results of case 23 with that of case 8 the T/T_{th} ratio was decreased from 0.46 (Case 8) to 0.37 in Case 23 (optimal inlet and outlet baffle locations). However, the C/C_0 increased from 1.83 (Case 8) to 2.53 (Case 23). T_{50}/T_{th} ratio decreased from 0.403 in Case 8 to 0.401 in Case 23; however, value of t_{10}/T also decreased from 0.216 to 0.185. This means that the outlet baffle at this location has negative impact on the hydraulic characteristics of the tank. This could be ascribed to the turbulence that was formed due to narrow distance between the outlet baffle wall and tank wall. This interpretation could be supported by the dye evolution photos (Fig. 13). As shown in the figure, the dye plume was formed at the outlet (left photo, case 8). However, the plume is dispersed at the outlet baffle and circulation zone is formed near the bottom (right photo).

The outlet baffle position was shifted further toward the inlet. The longitudinal location (s2) was increased from 5% to 7% with the vertical position (h2) of 16%, 33%, 65% and 75% (Cases 26–29). Fig. 14 shows flow through curves (FTCs) of case 26–29. As shown in the figure, peak concentration ratios (C/C_0) were 2.06, 2.67, 3.02 and 1.95 at bottom contraction of 16%, 33%, 65% and 75% respectively. The corresponding residence time ratios (T/T_{th}) were 0.50, 0.37, 0.37 and 0.25. As shown in Table 6, Case 26 (7, 16%) has higher value of t_{10}/T and lower value of t_{90}/t_{10} compared with Cases 26–29. The higher value of t_{10}/T represents lower short-circuiting conditions.

The interpretation is similar to that described for previous cases. Based on that, the best vertical position (h2) of outlet baffle at longitudinal position of 7% L is 16% of the tank depth (Case 26). Comparing the results of Case 26 with tht of Case 8, the T/T_{th} was increased from 0.46 (Case 8) to 0.50. The T_{50}/T_{th} ratio increased from 0.403 in Case 8 to 0.448 in Case 26; however, value of t_{10} also decreased from 0.216 to 0.164. This could be ascribed to the minimization of dead zones and enhanced flow pattern occurred by adding the outlet baffle [3,39,41].

As in Fig. 15, longitudinal positions of the outlet baffle (s2) were increased further to be 15% (Cases 30–33) at h2 similar to that of previous cases (16%, 33%, 65% and 75%). Peak concentration ratios (C/C_0) were 1.73, 1.63, 1.31 and 1.95 at contraction of 16%, 33%, 65% and 75% respectively. The corresponding residence time ratios (T/T_{th}) were 0.55, 0.41, 0.41 and 0.25. As shown in Table 6, Case 30 (15%, 16%) has higher value of t_{10}/T in comparison with Cases 26–29. The higher value of t_{10}/T represents lower short-circuiting conditions.

Based on that, the best vertical position (h2) of outlet baffle located at longitudinal position of 15% L is 16% of the tank depth (Case 30). Comparing the results of Case 30 with that of Case 8 , the T/T_{th} was increased from 0.46 (Case 8) to 0.55 (Case 30). However, the C/C_0 decreased from 1.83 (Case 8) to 1.73 (Case 30). The T_{50}/T_{th} ratio increased from 0.403 in Case 8 to 0.521 in Case 26; however, value of t_{10}/T also decreased from 0.216 to 0.218. This could be ascribed to the minimization of dead zones enhanced flow pattern occurred by adding the outlet baffle [3,39,41].

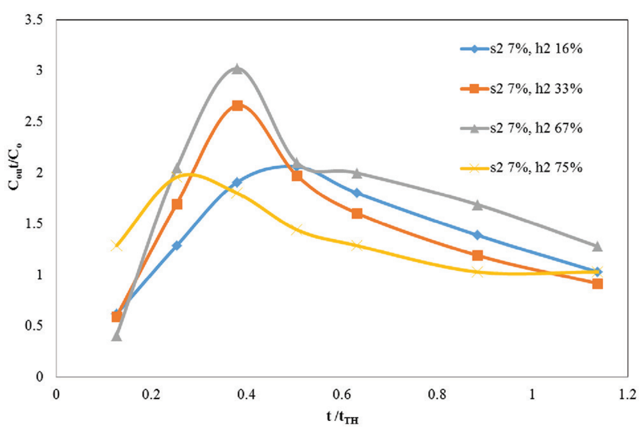

Fig. 14. Time of maximum concentration for different outlet baffle vertical positions (h2 = 16%, 33%, 65% and 75; and s2 = 7% of the length).

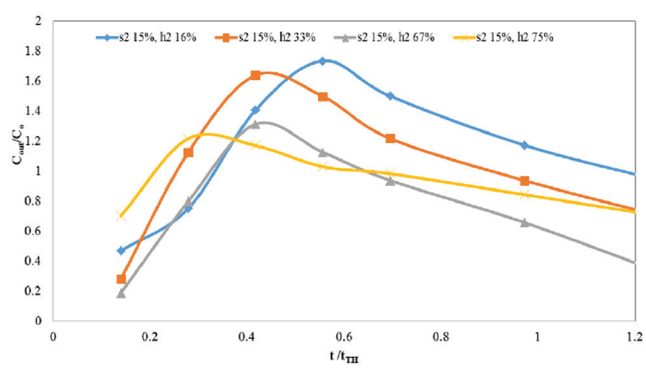

Fig. 15. Time of maximum concentration for different outlet baffle vertical positions (h2 = 16%, 33%, 65% and 75; and s2 = 15% of the length).

The outlet baffle best longitudinal and vertical positions for Cases 19, 23, 26 and 30 in addition to Case 8 (without outlet baffle) are compared together as presented in Fig. 16. From the figure, the case that has outlet baffle is located at 15% of the length and 33% of tank depth upward from the bottom appeared to be the optimum outlet baffle location that has the maximum residence time ratio (T/T_{th}). The figure shows that the use of outlet baffle in most of the cases significantly improved the settling tank hydraulic characteristics. Table 7 shows the hydraulic parameters of Cases 19, 23, 26 and 30 in addition to Case 8 (without outlet baffle). As shown in the table, Case 8 (5, 67%) has higher values of t_{10}/T and lower value of t_{90}/t_{10} which mean lower short-circuiting and lower mixing conditions of the flow occurred at this position.

3.3. CFD modelling

Computational fluid dynamics (CFD) method is a powerful tool that used to simulate the hydrodynamics and flow behaviour in a sedimentation tanks. A two-dimension geometrical model of rectangular settling tank has been developed in design modular associated with ANSYS workbench. The contours of velocity magnitude and kinetic energy that describe the hydraulic performance of the settling are obtained from the CFD modelling.

The velocity contours in a no-baffle tank and the tank in which the inlet/outlet baffles are located at the optimum position are shown in Fig. 17. Fig. 17a shows velocity magnitude for case 1 where no baffle is used. The figure shows high velocity magnitude at the tank surface. The strong surface current generated by the high velocity magnitude could push the particles to flow out of the tank directly without enough time for settling [33]. It also shows high velocity magnitude at the bottom and middle of the tank. The high velocity at the tank bottom could form re-circulating current and cause re-suspension of the settled particles in the bottom of the tank [42]. Re-circulating current leads to dead zone formation and hence effective volume of settling tank will decrease. Re-circulating current cause mixing which may bring bottom settled particles back to tank surface [43]. Fig. 17b shows velocity magnitude for case 8 where inlet baffle is located at the optimum location (h1: 67% and s1: 5%). Due to effect of inlet baffle, the high velocity magnitude at the tank surface is significantly reduced. No significant improvements in the velocity magnitude due to the use of outlet baffle (Fig. 17c).

Kinetic energy is an important parameter for CFD simulation of the settling tank [44]. Strong kinetic energy may cause re-suspension of the settled particles, so that one major objective of the use of inlet baffle in the settling tank is the kinetic energy reduction [42–44]. As shown in Fig. 18a when no-inlet baffle is used, the kinetic energy spread on the surface of tank inlet. This kinetic energy is dissipated when the inlet baffle is used (Fig. 18a). There is no significant impact on the kinetic energy due to the presence of outlet baffle (Fig. 18c).

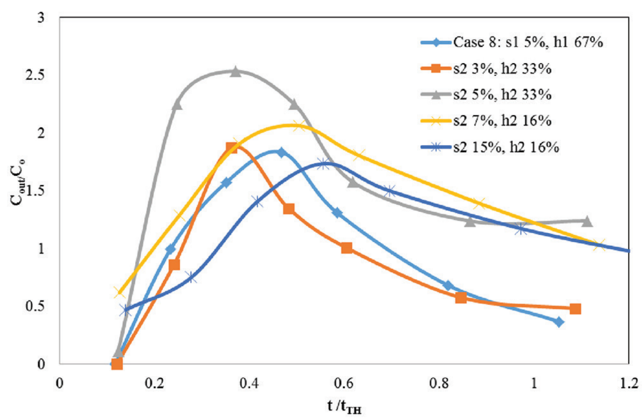

Fig. 16. Comparison between different outlet baffle best longitudinal and vertical positions.

Table 7
Hydraulic parameters from RTD curve for different outlet baffle best longitudinal and vertical positions

Cases	t_{10}/T	t_{90}/t_{10}	T_{max}/T	t_{50}/T
8	0.216	3.108	0.46	0.404
19	0.205	3.882	0.36	0.393
23	0.185	4.833	0.37	0.401
26	0.164	5.423	0.50	0.448
30	0.219	4.603	0.55	0.521

4. Conclusions

- The use of inlet baffle at the optimum position significantly improved the settling tank performance in terms actual residence time and presence of dead zones.

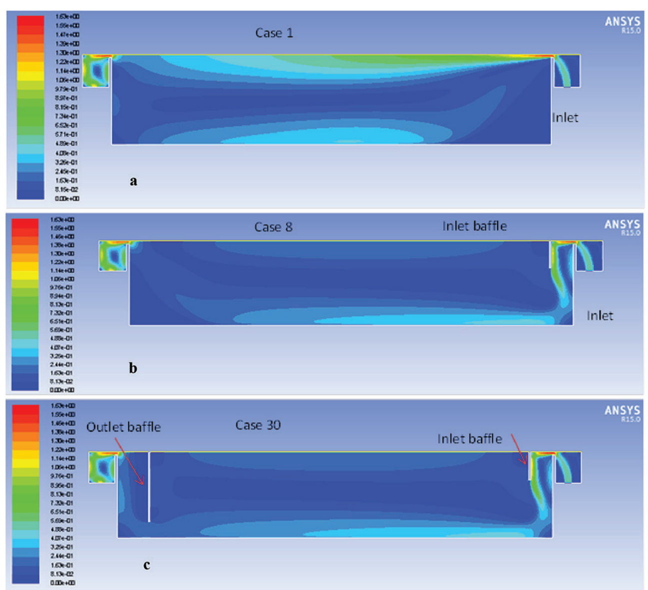

Fig. 17. Computed velocity vector contours at no baffle (a) Case (1), (b) inlet baffle Case (8), (c) inlet and outlet baffle Case (30).

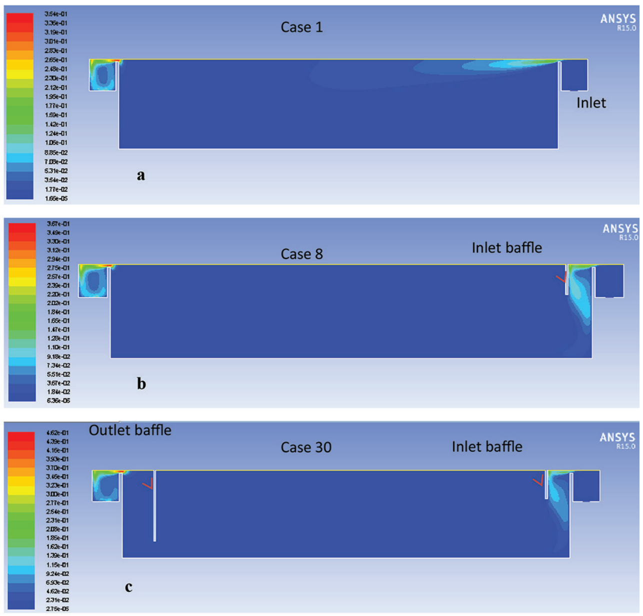

Fig. 18. Computed contour of kinetic energy at no baffle (a) Case (1), (b) inlet baffle Case (8), (c) inlet and outlet baffle Case (30).

- The optimum inlet baffle position is 5% of the tank length (L) from the inlet and 67% of tank depth upward from the bottom.
- The use of outlet baffle at the optimum position is also improved the settling tank hydraulic performance.
- The optimum position of the outlet baffle is to be placed at 15% L from the outlet and 16% of tank depth upward from the bottom.
- Significant reduction in dissipation of kinetic energy and reduction of velocity magnitude at the tank inlet due to the use of inlet baffle are proved by CFD modelling.

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