PERFORMANCE OPTIMIZATION OF RECTANGULAR SETTLING TANKS IN SMALL WATER TREATMENT PLANTS BY NUMERICAL APPROACH

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ABSTRACT

Separation of suspended and colloidal materials from water and wastewater by settlement is one of the most widely used process in water and wastewater treatment. Hydraulic retention time is a main parameter for design and optimization of any water treatment tank or reactor. Determination of the retention time distribution at all different locations within the tank gives information about the possibility of presence of dead zones or and short circuits. The presence of dead zones decrease the effective volume of the tanks that may almost result in a short circuit between the inlet and outlet of the tank. some part of the flow exits the tank without spending the retention time required for settling. On the other hand, it also induces high turbulence intensity in other regions, which not only decreases the possibility of particle aggregation and deposition, but may also causes solids re-stabilization. A uniform flow field is essential to increase the efficient performance of settling tank. This enables particles to settle at a constant velocity and in less time. Serious design and selection of a suitable inlet baffle configuration for settling tanks is one method to decrease the regions and size of the dead zones which shall improve the process performance. The objective of this paper is to study the performance of diffusion drums inlet baffle for settling tanks. In this paper, a computational model has been mapped to the commercial FLUENT® solver and applied to simulate the flow within a 3D rectangular water tank. Finally, numerical results shall demonstrate the optimum hydraulic diameter ratios range for diffusion drums sizing.

Keywords: retention time, settling tank design, baffles, dead zones, CFD.
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1 INTRODUCTION

A publicly owned treatment works (POTW) are designed based on large quantities of water or wastewater which requires large foot print and structures. One of these structures is the settling tanks which may be rectangular or circular. The inlet and outlet structures occupy a percentage of this foot print where the flow should be distributed in the three dimensions. Based on practical approach; in small water and wastewater treatment plants which are mostly privately owned the inlet and outlet structures is a vital matter which should be optimized to have lower dead zones and best available distribution of the velocity profile inside the tank with - of course - lower foot print of total occupied area.

This paper is study the validation of using this diffusion drum as an inlet baffle. Diffusion drums with different hydraulic diameters is studied with comparison with rectangular inlet baffle, and in case of not using inlet baffle.

2 SETTLING AND RE-SUSPENSION VELOCITIES

Settling tanks are designed to reduce the velocity of water so as to permit suspended solids to settle out of the water by gravity. The velocity with which a particle in water will fall under the action of gravity depends upon the horizontal flow velocity of the water, the size, relative density and shape of the particle and the temperature of the water. The theoretical velocity of falling spherical particles in slowly moving water V_o (m/s), is given by Stokes' Law which is a simplified form of Newton's Law:

$$v_o = \frac{g}{18} \frac{\rho_o - \rho_w}{\mu} d^2 \quad (1)$$

where g = 9.81 m/s^2, ρ_0 is the density of the particles, ρ_w is the density of the fluid, d is the diameter of the particles in m and μ is the dynamic viscosity of water in pa.s, which varies with the temperature of the fluid.

Apart from the settling rate in still water it is, of course, essential that once a particle has reached the base of the tank it shall not be re-suspended by the velocity of flow of water over the bed. Camp (1946), gives the critical velocity V_C (m/s) required to start motion of particles of diameter d (mm) as:

$$v_C = \left(\frac{8\beta g(\rho_o - \rho_w)}{10^3 f \rho_w} d \right)^{1/2} \quad (2)$$

where f is the friction factor in (4flv^2/^{2}gd), β is in the range 0.04-0.06 for sticky flocculent materials, and 0.10-0.25 for sand and g = 9.81 m/s^2.

There is general agreement that this velocity should not be more than 0.3 m/s to allow sand grains to settle. This is, of course, too high a velocity for the settling of particles of light relative density (1.20 and less). At 0.2 m/s faecal matter, i.e. organic matter, will begin to settle (Twort, A., C. et al 2000).

3 IDEAL SETTLING TANKS

As shown in "Fig. 1" the ideal settling tank shall have inlet zone, outlet zone which have the same importance of settling and sludge zones. There is certain critical settling velocity such that all particles settling faster than this value will be removed. The term Q/A_S is known as the surface loading rate or overflow rate and is equal to the critical settling velocity V_o where Q is the discharge rate and A_s is the surface area (Gregory 2006).

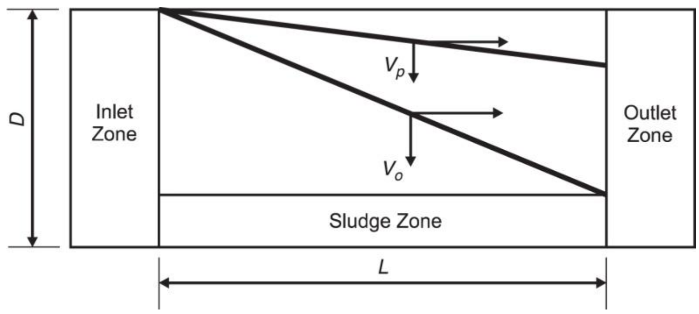


Figure 1. Typical Settling Tank Inlets

To approach this ideal as nearly as possible, the retention time τ for each particle of water is the same, equal to V/Q where V is the volume of the tank. Also retention time τ is equal to the length of the tank divided by the horizontal velocity. This relation is valid for ideal settling tanks.

A terminal velocity V_o is selected for the sizing of a settling tank so that all particles having a velocity equal to or greater than V_o are removed. In the ideal tank; it is assumed that particles entering the tank are evenly distributed over the inlet cross section (Nalco 2008). If all flow enters a settling basin at one point, the particles must be distributed across the entire basin width and depth before the flow velocity, V_o is minimized. Depending on the efficiency of distribution, the velocity at some point could be many times faster than the velocity at other one (Alley 2007).

4 INLET BAFFLES

Typical settling tank inlets are shown in “Fig. 2”. These inlets may be not feasible in small water and wastewater treatment plants due to required foot print of these inlet structures

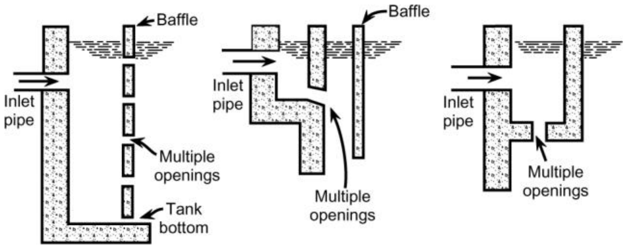


Figure 2. Typical Settling Tank Inlets

A combined photo of existed settling tank with dimensions 5 m Length * 5 m Width * 4 m Height and two views of installed diffusion drum is shown in "Fig. 3". In these photos; a half cylindrical part is installed which called in practical field "diffusion drum" which is dissipate the energy of inlet flow and distribute the flow inside the tank in half radial direction.

Figure 3. A combined photo of existed settling tank with dimensions 5 m Length * 5 m Width * 4 m Height and two views of installed diffusion drum

According to the investigations of Camp and Swamee and Tyagi the investment costs of settling facilities contribute to a large portion (typically one-fourth to one-third) of the total cost of treatment plant construction. A uniform flow field is essential to increase the efficient performance of settling tank. This enables particles to settle at a constant velocity and in less time. The existence of circulation regions (dead zones) reduces the sedimentation of particles and has major influence on the hydraulic condition of flow field inside the settling basins. Circulation zones are named as dead zones in tanks because, in these regions, water is trapped and particulate fluid will have less volume for flow and sedimentation. According to this, the existence of large circulation regions will lower tank performance (Heydari 2013).

Zhang (2014) studied a different configuration of full width rectangular inlet baffle. He proves that re-circulating current is always existed in sedimentation tanks, circulation zones, dead zones occupy the effective sedimentation volume, so that the sedimentation tank will have less volume for settling, thereby the existence of re-circulating current or circulation zones will reduce tank efficiency.

Different methods are proposed for reducing the effects of these problems and increasing the tank performance. A common approach for decreasing settling tanks problems is to use baffles which can reduce effects of the unfavorable phenomena such as short circuiting between inlet and outlet and density currents in settling tanks. The baffles usually install at the bottom or surface of the rectangular settling tanks. Various studies have been done on the effects position and size of baffles on the flow and hydraulics of settling tanks. In settling tanks for increasing their sedimentation performance, baffles are usually placed in the front of inlet opening (Heydari 2013).

Shahrokhi et al (2011 a), investigated the effects of baffle location on the flow field. Using CFD and VOF methods, they developed a numerical simulation of flow in the tank through the FLOW-3D® software. Results show that the installation of a baffle improves tank efficiency in terms of sedimentation. The baffle acts as a barrier, effectively suppressing the horizontal velocities of the flow and reducing the size of the dead zones. A baffle also reduces turbulent kinetic energy and induces a decrease in maximum magnitude of the stream-wise velocity and upward inclination of the velocity field compared with the no-baffle tank. On the basis of these results, the baffle must be placed near the circulation region.

Shahrokhi et al (2011 b) studied the baffle effect on the flow in a rectangular primary sedimentation tank using numerical investigation. They conclude that circulation regions may appear with size sensitive to the position of the baffle when a baffle is used in the tank. The best position for the baffle is obtained when the volume of the circulation zone is minimized or the dead zone is divided into smaller parts. Thus, the best position for the baffle may lead to a more uniform distribution of velocity in the tank and minimize dead zones. Small recirculation zones, which are important to sedimentation, are also found near the entry and exit weir.

Razmi et al (2009) performed an experimental and numerical work to investigate the effects the baffle position on the flow field. In laboratory, a test rig was conducted to find the effect of the baffle position on the velocity profiles. Then, using CFD, a numerical simulation of flow in the tank was developed by Fluent software. Using the experimental data, the numerical results were verified. Finally, the optimal location of the baffle was found numerically. Results show that this baffle can reduce the size of the dead zones and turbulent kinetic energy in comparison with the no-baffle condition.

Egyptian Housing & Building National Research Center (2008) considered the inlet and outlet baffles in the description of settling tanks for both water and wastewater treatment in the latest edition of Egyptian Code for the Design and Implementation of Water, Sewage Treatment Plants, and Sewage Lift Stations.

Goula (2007) studied the influence of a feed flow control baffle. The 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. Although the increase in the overall effectiveness by this baffle may show only a small change, this actually reflects a reduction of the effluent solids of estimated around 85%. He concluded that CFD can be a powerful tool for troubleshooting problems, particularly those associated with flow patterns in a sedimentation tank.

Water that by-passes the normal flow path through the basin and reaches the outlet in less than normal retention time occurs to some extent in every basin. It is a serious problem, causing floc to be carried out of the basin due to the shortened sedimentation time. The major cause of short-circuiting is poor inlet baffling (Adams, Jr. et al 2000).

5 SHORT CIRCUITING

The flow should be distributed uniformly across the inlet of the basin "Fig. 4". The solids removal efficiency of a settling is reduced by the following conditions (Adams, Jr. et al 2000):

- Eddy currents induced by the inertia of the incoming fluid.
- Surface current produced by wind action "Fig. 4 D". The resulting circulating current can short-circuit the influent to the effluent weir and scour settled particles from the bottom.
- Vertical currents induced by the outlet structure
- Vertical convection currents induced by the temperature difference between the influent and the tank contents "Fig. 4 B, C".
- Density currents causing cold or heavy water to under run a basin, and warm or light water to flow across its surface "Fig. 4 B".
- Currents induced by the sludge scraper and sludge removal system.

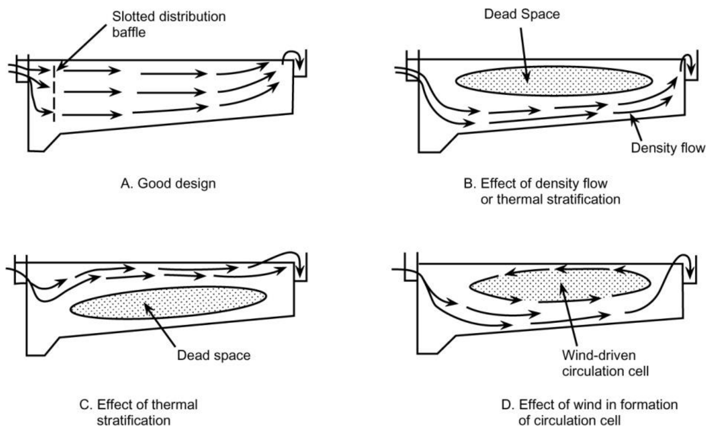


Figure 4. Flow patterns in rectangular sedimentation tanks

6 NUMERICAL MODEL

In this study; GAMBIT® software is used to mesh and assign the continuum type and boundary conditions of the model. Then the model is solved using Fluent® Software.

6.1 Model Meshing

As shown in "Fig. 5" the isometric of settling tank model and a section with dimensions of this model which is modeled and meshed using Gambit Software.

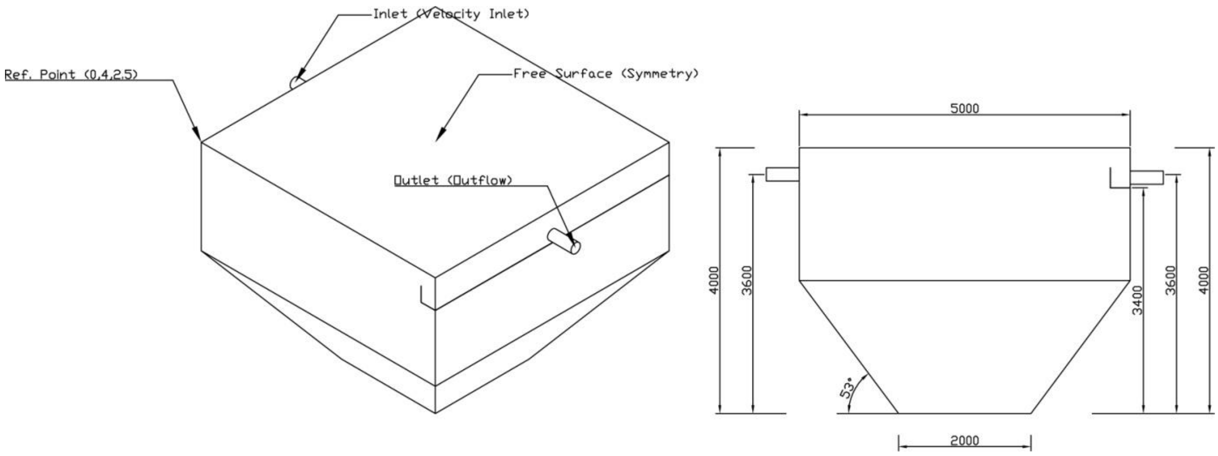


Figure 5. Settling Tank Model 5*5*4 m

6.2 Boundary Conditions

Solving the model is based on steady state viscous k- epsilon model. As the flow is considered balanced; the steady state model shall be valid. The boundary conditions are assigned as per table 1.

The turbulence intensity shall calculated using the following equations:

$$\mathrm{Re} = \frac{vD}{\gamma} \tag{3}$$

$$TI = 0.16\,\mathrm{Re}^{-1/8} \tag{4}$$

where Re is the Reynolds Number, D is the diameter m, γ is Kinematic Viscosity m^2/s, and IT is the Turbulent Intensity.

Table 1. Zones Boundary Condition Types

Zone	Boundary Condition Type
Inlet	Velocity Inlet
Outlet	Outflow
Free Surface	Symmetry
Walls	Walls (0.1 mm Roundness)

This tank has the following specification: gross volume is 76 m^3 , the net volume is 68.5 m^3, and the surface area is 25 m^2. The inlet pipe is 0.2 m in diameter with area 0.03142 m^2.

By applying equations 3, 4, 5, 6, and 7 by using the inlet flow rate 30 m^3/hr; we can get the values as per table 2.

Table 2. Velocity Inlet Boundary Conditions

Feed Flow [m^3/hr]	Surface Loading [m/hr]	Retention Time [hr]	Inlet Velocity [m/sec]	Re	TI %
30	1.2	2.283	0.265	57664.83	4.064

6.3 Baffle Cases

The following cases shall be studied in this paper where all baffles are 1 m depth from free surface:

- Case 01: Inlet zone without inlet baffle.
- Case 02: Inlet zone with rectangular inlet baffle 5 m length.
- Case 03: Inlet zone with half cylindrical inlet baffle 0.5 m diameter.
- Case 04: Inlet zone with half cylindrical inlet baffle 1.0 m diameter.
- Case 05: Inlet zone with half cylindrical inlet baffle 1.5 m diameter.
- Case 06: Inlet zone with half cylindrical inlet baffle 2.0 m diameter.

6.4 Post Processing

The results shall be limited to:

- X- velocity VS x-position on three different levels at the middle of the tank. z value at the middle of the tank is 0. so, the line shall be labeled with its level at z=0 as following: y=0.5 @ z=0, y=2.0 @ z=0, and y=3.5 @ z=0.
- X- velocity VS x-position on three different levels at the half middle of the tank. z value at the half middle of the tank is 1.25. so, the line shall be labeled with its level at z=1.25 as following: y=0.5 @ z=1.25, y=2.0 @ z=1.25, and y=3.5 @ z=1.25.
- Velocity magnitude vectors over z plane=0 and y plan=3.5.
- A secondary axis shall be used in case of have different velocity ranges.

7 RESULTS AND DISCUSSIONS

7.1 Inlet Zone Without Baffles

The following "fig. 6" shows the velocity profile at 30 m^3/hr in X direction. This profile shows that velocity over y=3.5 m at the middle of the tank is very high compared with other velocities which gives an indication that water that by-passes the normal flow path through the basin and reaches the outlet in less than normal retention time. Furthermore; the velocity at y=3.5 at z=0 is very high compare to velocity at y=3.5 at z=1.25 which proves the short circuiting occurs in the tank.

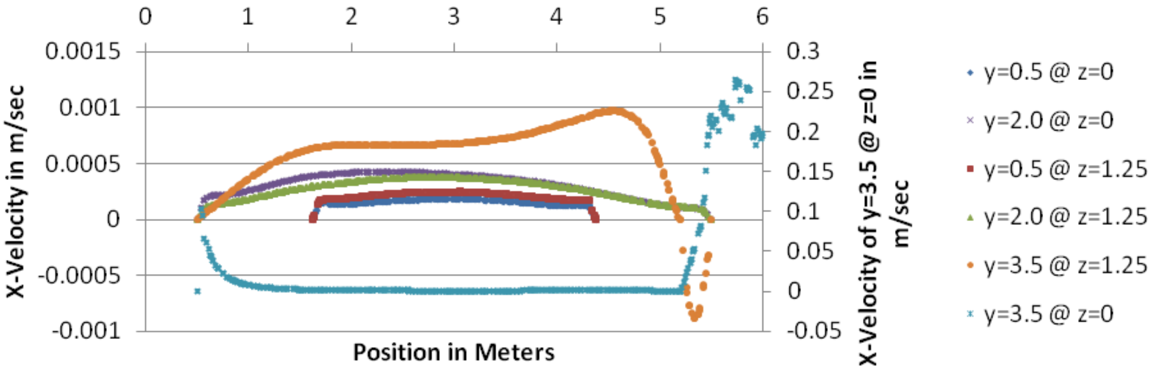
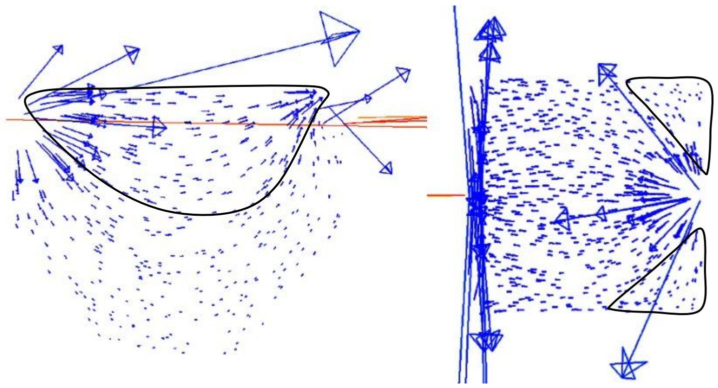


Figure 6. X Velocity VS X Position at Different Y & Z Values - Case 01

In "Fig. 7 A" the velocity magnitude vectors at z=0 plane near to free surface have large velocity values. Also in "Fig. 7 B" at y=3.5 plane the velocity inlet takes a conical shape which have high velocities magnitude near to the middle of the tank.



(A) **(B)**

Figure 7. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 01

7.2 Inlet Zone With Rectangular Baffle 5 m Length

This profile "Fig. 8" shows that velocity based on 30 m^3/hr over y=3.5 m at the middle of the tank is also very high (over re-suspension velocity) with compare with other velocities which gives an indication that Water that by-passes the normal flow path through the basin. Other velocities are varies along the tank in the same range which is under the critical re-suspension velocity.

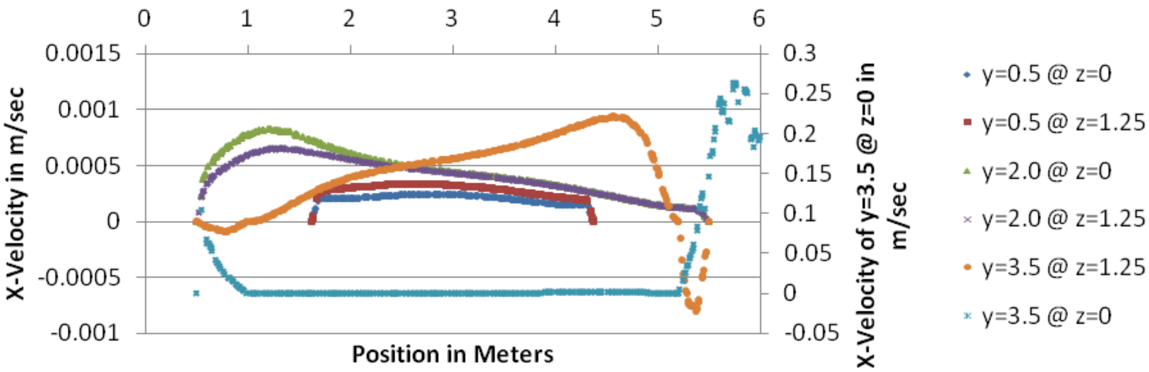
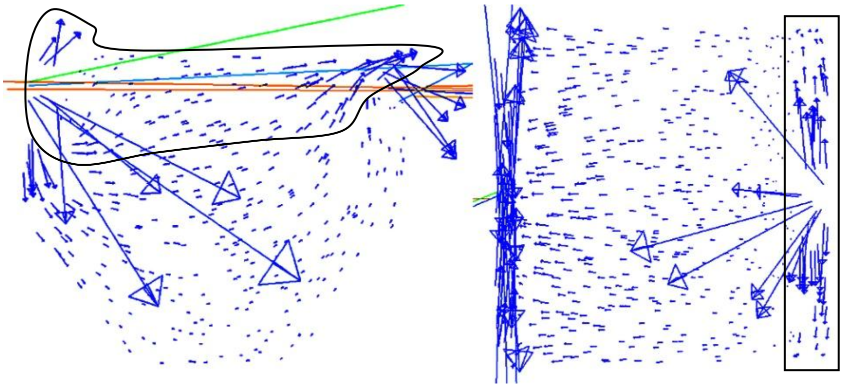


Figure 8. X Velocity VS X Position at Different Y Values - Case 02

In "Fig. 9 A" the velocity magnitude vectors have an almost uniform distribution but the velocities vectors near to free surface still have large magnitude. In "Fig. 9 B" the inlet baffle forced the influent to flow perpendicular to the inlet pipe. Although no dead zones appears but the whole area of the baffle is considered an inlet zone.



(a) (b)

Figure 9. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 02

7.3 Inlet Zone with Half Cylindrical Baffle 0.5 m Diameter

In "Fig. 10" the velocity based on 30 m^3/hr over y=3.5 m at the middle of the tank is within the range of other velocities. A range of the Velocities at y=3.5 are negative values which means that there is a recirculation in the planes near to the free surface.

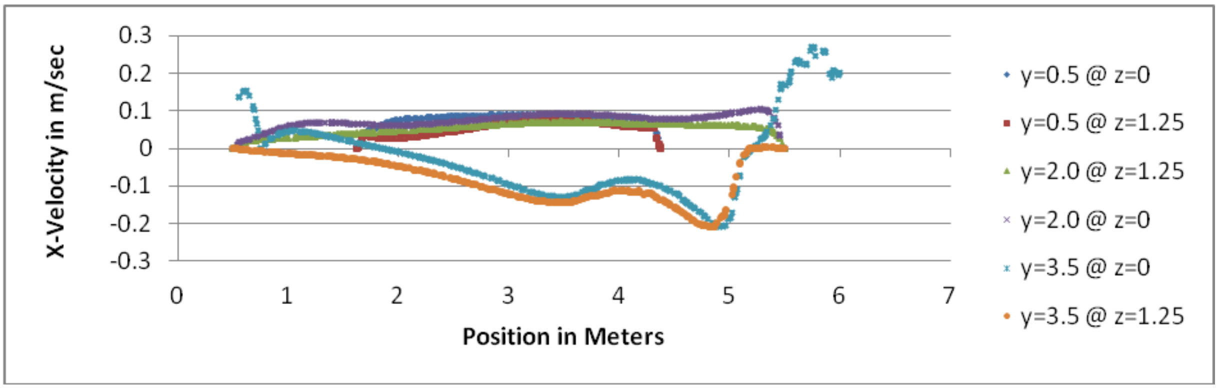
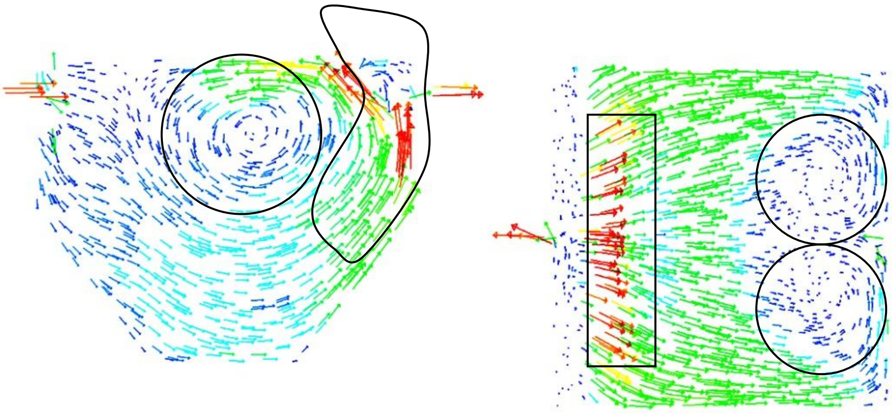


Figure 10. X Velocity VS X Position at Different Y Values - Case 03

In "Fig. 11 A" a circulation zone is shown in the middle of the tank, and the whole flow is circulated inside the tank. In "Fig. 11 B" the velocity vectors have a tight range of velocity but in front of the inlet baffle a two circulation zones are existed beside a reverse flow caused by the circulation zones.



(a) (b)

Figure 11. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 03

7.4 Inlet Zone with Half Cylindrical Baffle 1.0 m Diameter

In "Fig. 12" the velocity based on 30 m^3/hr over y=3.5 m at the middle of the tank has a high velocity. Also, at level y=2 there are high velocities area due to recirculation in the tank in this region.

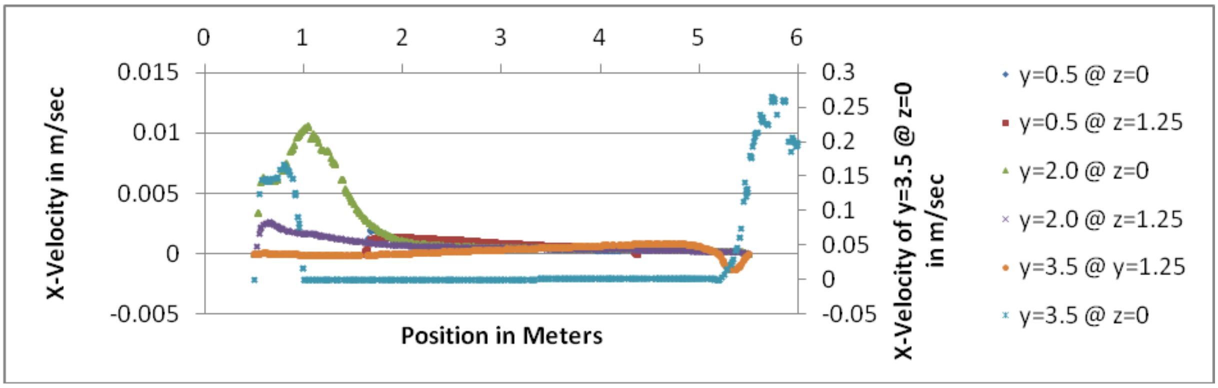
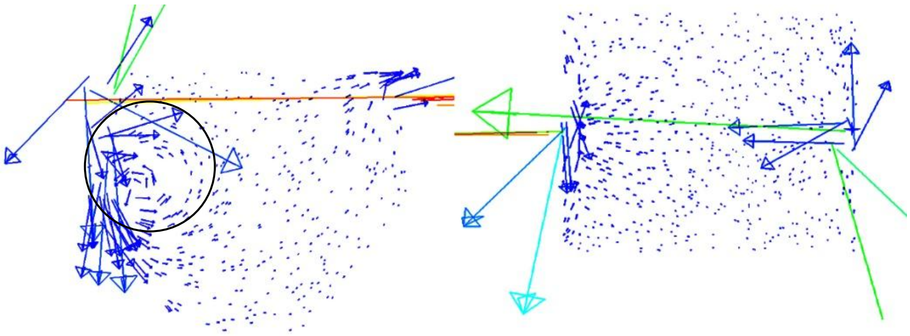


Figure 12. X Velocity VS X Position at Different Y Values - Case 04

In "Fig. 13 A" a circulation zone existed at the inlet zone, and the flow profile in the rest of the tank at z=0 plane is considered well distributed. In "Fig. 13 B" the velocity vectors has an area of a reverse flow in front of outlet weir area.



(a) (b)

Figure 13. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 04

7.5 Inlet Zone with Half Cylindrical Baffle 1.5 m Diameter

In "Fig. 14" the velocity based on 30 m^3/hr over y=3.5 m at the middle of the tank has a high velocity. At level y=2; the flow is considered well distributed.

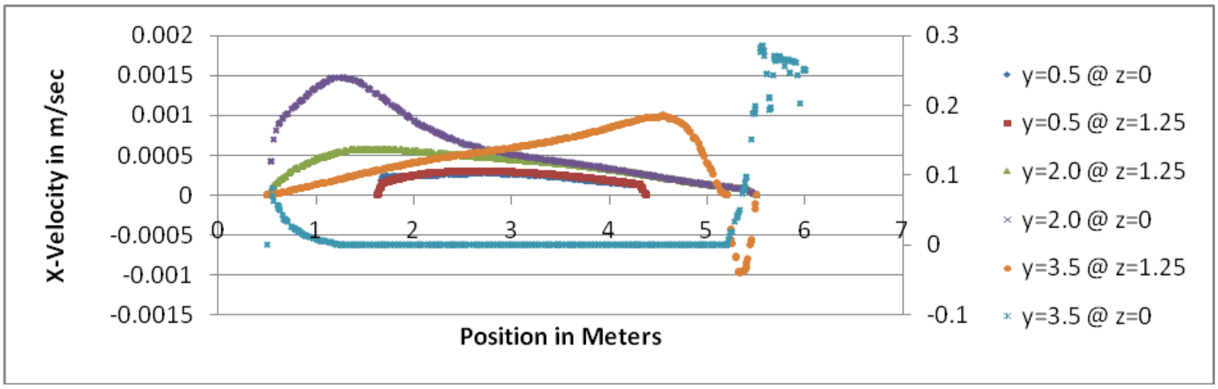
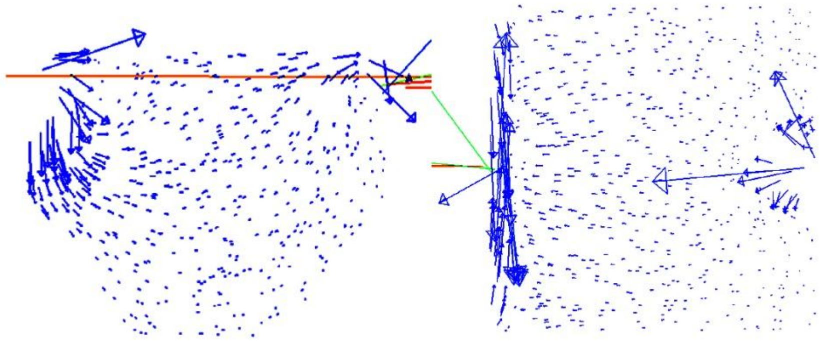


Figure 14. X Velocity VS X Position at Different Y Values - Case 05

In "Fig. 15 A" the velocity vectors at z=0 plane which is considered well distributed with high velocities zone near to the free surface. In "Fig. 15 B" the velocity vectors are well distributed.



(a) **(b)**

Figure 15. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 05

7.6 Inlet Zone with Half Cylindrical Baffle 2.0 m Diameter

In "Fig. 16" the velocity based on 30 m^3/hr over y=3.5 m at the middle of the tank has a high velocity. At level y=2; the flow is considered well distributed.

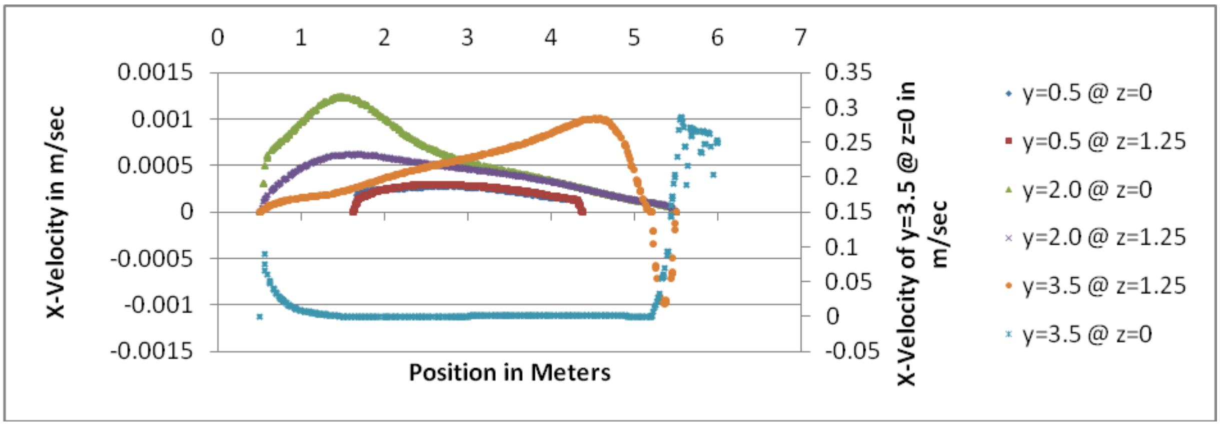
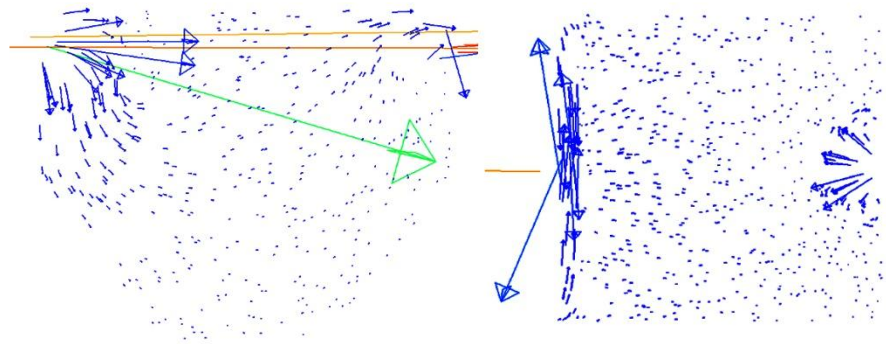


Figure 16. X Velocity VS X Position at Different Y Values - Case 06

In "Fig. 17 A" the velocity vectors at z=0 plane which is considered well distributed with high velocities zone near to the free surface. In "Fig. 17 B" the velocity vectors are well distributed.



(a) **(b)**

Figure 17. Velocity Magnitude Vectors (a) at Z=0 Plane (b) at y=3.5 - Case 06

7.7 Results Summary

Hydraulic diameter of the settling tank with surface area 25 m^2 is equal to 5.642 m. The average horizontal velocity inside the tank is 0.00049 m/sec. Table 3 shows the summary of baffles cases considered in this paper.

Table 3. Baffles Hydraulic Specifications

Baffle Type	Effective Surface Area [m^2]	Hydraulic Diameter [m]	Hydraulic Diameter Ratio	Mean Velocity m/sec at z=0 Plan			
				X- Vel. at 3.5	Y- Vel. at 3.5	X- Vel. at 2.0	Y- Vel. at 2.0
Rectangular 5 m width	2.5	1.784	31.623%	0.0311	0.0002	0.00044	-2.59E-05
Half Cylindrical 0.5 m diameter	0.0982	0.354	6.267%	-0.0182	0.011453	0.074075	0.0164
Half cylindrical 1.0 m diameter	0.393	0.707	12.533%	0.0375	0.000171	0.002068	-0.00165
Half cylindrical 1.5 m diameter	0.884	1.061	18.8%	0.0354	0.00014	0.00065	-0.000242
Half cylindrical 2.0 m diameter	1.571	1.414	25.1%	0.0372	0.00069	0.0006	-0.000242

As per table 3; the negative sign refer to negative direction of the flow. For y-direction velocity; the negative sign give an indication of the flow in settling direction. The rectangular inlet baffle has a good velocity distribution but it requires high hydraulic diameter ratio (31.6 %) to achieve these results. A half cylindrical inlet baffle with diameter 0.5 m (hydraulic diameter ratio 6.2%) shall excluded as a circulation zone is created inside the tank. Also, inlet baffle with diameter 1.0 m (hydraulic diameter ratio 12.5%) shall not considered due to the circulation zone under the baffle with high velocities comparing with design velocities in both x, y directions.

Both of inlet baffles with diameters 1.5 m (hydraulic diameter ratio 18.8%), and 2.0 (hydraulic diameter ratio 25.1%) have an acceptable velocity profiles but in case of inlet baffle with diameter 1.5 m a lower ratios between mean velocities and design average velocities at y=3.5 has obtained.

8 CONCLUSIONS

This study has validate the importance of inlet baffle and specially the diffusion drum in small water treatment plants. The diffusion drum usage is prove its ability to distribute the flow with foot print saving of inlet zone. The 3D modeling creates an easy way to investigate the velocity contours and vectors in the entire tank.

A diffusion drum inlet baffle with hydraulic diameters range 18.8:25.1% is recommended to be used in small water treatment settling tanks. Choosing the optimum inlet baffle approaches the ideal case of settling tank which means that actual detention retention time approaches the theoretical retention time.

9 RECOMMENDATIONS

It is highly recommended to consider the inlet and outlet baffle functions, types, design criteria which shall maximize the performance with an economic influence in Egyptian code for the design and implementation of water, sewage treatment plants, and sewage lift stations.

A recommendation for further works to study the diffusion drum influence on the treatment performance and quality experimentally compared with theoretical study.

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