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Numerical Analysis of Circular Settling Tank

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Abstract. Nowadays, settling tank's removal efficiency is one of the most crucial matter in all Water or Wastewater Treatment Plants (WTPs or WWTPs). The unit can affect a WWTP performance and improve effluent quality provided. In this paper, geometrical aspects of a settling tank were numerically analyzed via tracer curves, finite volume method and Ansys-cfx software in which, baffle depth and diameter of a settling tank were assessed. Firstly, a previous study was similarly remodeled to verify the simulation results. The impact of tank depth variation has been numerically assessed where the outcomes showed that deeper tank could raise discharge time or Hydraulic Retention Time (HRT). Thus, extensive discharge time may result in less polluted effluent degrading more solids. However, the tank should not be considered too deep regarding economic issues. Moreover, the differential effect of baffle height was analyzed and indicated that lower height is more useful to boost HRT. Investigation of tank diameter changes also revealed that wider diameters bring broader HRT.

Keywords: Settling Tank, Tank Depth, Tank Diameter, Tracer Curve, Finite Volume Method.

1 Introduction

Over the past decades, Water and Wastewater Treatment Plants (WWTPs) have drawn governments' attention to water especially, environmental hazards originating from grey and sewage runoff throughout urban areas. In this regard, treatment processes can be optimally designed and operated. Therefore, one of the most critical stages in WWTPs is sedimentation in settling tanks, used to degrade and to remove organic matters and solids. Turning to the research background shows that several models have been addressed to simulate and analyzed sedimentation process numerically. In an attempt to simplify methods, some assumptions were effectively used to evaluate flow pattern movement as well as solids and particles in settling tanks.

According to previous studies, mathematical models are often applied instead of analytical solution ones to reach precise flow characteristics (Imam et al., 1983). Moreover, three methods are suggested to have an appropriate description of flow pattern movement and characteristics (Kynch, 1952). Firstly, one-dimensional model is introduced in which solids vertical movement is considered (Kynch, 1952). Secondly, two dimensional model is presented so the vertically and horizontally solids movement described. The matter which was once used to simplify the three dimensional model (Imam et al., 1983). Ultimately, three dimensional model is another way of description having more benefits thanks to orient the flow pattern. Liu and Garcia were developed a three-dimensional (3D) numerical model to simulate large primary settling tanks in which

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tracer study was applied to investigate the tank's residence time (Liu and Garcia, 2010). The model was implemented on a settling tank in Chicago where locates in The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). Through the case study, a computational fluid dynamics (CFD) model simulated solids removal efficiencies. The results of the research model were used to establish the design basis for tank side-water depth, inlet feed-well dimensions, etc. Liu and Garcia model outcomes can be capitalized to decrease the cost of construction via optimized settling tank.

Vahidfar et al. in 2018 investigated and modeled a rectangular settling tank in full scale by CFD method to increase its efficiency. (Vahidfar et al. 2018). Zahabi et al. also in 2018 numerically investigated the geometry of rectangular reservoir to entrap sediments and they found optimum geometry (Zahabi et al. 2018).

There are a wide range of parameters which can be effective on settling tanks' performance. To illustrate that, Reynolds number, flow viscosity, type of hydraulic flow movement and tank dimension and design are the most significant factors in settling unit. Schamber and Larock were once used K-ε turbulence model in order to simulate settling stage applying for high Reynold's number and turbulent flow (Schamber and Larock, 1983). According to the study, coarse solids with high specific weigh leads to an increase in Reynold's number; therefore, this type of models are typically conducted for settling unit. Furthermore, a study showed that the k-ε turbulence model agreed well with some experiments in a simple geometries tank (Adams and Rodi, 1990). The quality of the computations, however, deteriorates with increasing flow complexity. In fact, the effects of flow curvature are mainly applied to clarify the differences between computation and experiment, which are not comprised in the standard k-ε model. Also, a mathematical model was used to predict the velocity and particles transport pattern in secondary rectangular tanks. The particle impacts called in terms of bottom current, surface return flow and solids concentration distribution of density stratification on the hydrodynamics were analyzed by (Zhou and Mc Corquodale, 1992). Consequently, the model was suggested to simulate the so-called density waterfall phenomenon in the front end of a settling tank.

It is suggested that effluent concentration changes by the velocities in the withdrawal zone (Mc Corquodale and Zhou, 1993). It is also revealed that there is more upward velocity in the withdrawal zone by decreasing dens-metric Froude number for a constant discharge showing the relationship between the dens-metric Froude number, hydraulic and solids load. The density of waterfall can entrain large volumes of the ambient fluid in the physical and numerical models (Zhou and Vitasovic, 1992). Also, the entrainment compensating flow rate has an indirect relation with the dens-metric Froude number. Furthermore, bottom strength of the current density, upward flow in the withdrawal zone, and recirculation all increase as dens-metric Froude number decreases due to the entrainment into the density waterfall.

Some research are also addressed an array of Computational fluid dynamics (CFD) modelling in the wastewater treatment (WWT) field (Dutta et al., 2014 and Zhang et al. 2016). For instance, although Wicklein et al has proposed a good modelling practice (GMP) for the wastewater application and it is based on general CFD procedures (Wicklein, et al., 2016).

Settling basins can be divided into two categories in terms of geometry, which are cubic and cylindrical shapes. In this regard, circular basins are better than rectangular ones in the sense that they need less area for construction, which might increase rectangular basins hydraulic efficiency (Stamou et al., 1989). In this study, some circular basins are considered as a modeled three-dimensional to simulate tanks' geometry and stream direction. Meanwhile, continuity and momentum equations are going to be analyzed via finite volume method, and density change of the particles is ignored. Eventually, tracer curve will be used to evaluate hydraulic efficiency in terms of basins' depth, and also tank diameter variation will be studied to assess repercussions.

2 Material and Methods

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An increase in settling time results in tank sedimentation efficiency in which considering appropriate size for tank's baffle and weir structure are the two ways of tanks' efficiency improvement. In this light, baffles may cause returning flow when flow reaches to baffle and weir structure, namely, extending distance of flow travel to discharge from basin tank. In this paper, the aim is to study and evaluate Chicago's basin tank which were evaluated in 2011 so as to analyze the basin's depth and diameter changes and its effects on effluent quality (Garcia, 2011). In this respect, tank properties are presented in table 1.

Table 1.

The Chicago tank is capable to maintain flow being treated into the basin by increasing retention time which happens while the weir is considered with shorter height causing long distance for flow to exist. Therefore, the mechanism triggers to provide more time for settling. On the other hand, flow is turning when reaches to the baffle wall. In this regard, the process is going to be evaluate via CEM-CFD model. The number of mesh considering through model is 12 million rectangular meshes (Tetra Unstructured Mesh) where the larger and shorter bases are 10 and 2 cm, respectively. The tank which was studied by Garcia, and flow lines along with tank meshes system are being shown in figure 1, 2, 3 and 4. It should be add that geometrical modeling was done by Ansys cfx software in the current study.

Fig 1.
Fig 2.
Fig 3.

In order to simplify the model and to obtain accurate result, some assumptions are considered including flow pattern is steady, temperature variation is ignored, flow temperature, density and velocity are assumed constant (T=20 C^o, Flow Density=998 Kg/m^3). In addition, boundary conditions are conducted in three main terms in which tank's surface is taken as slippery surface except the bottom of the tank, free surface is rigid and flow pressure is calculated hydrostatically, relative pressure at the end is zero, inlet is velocity radial control.

One way to calculate settling tank's efficiency is to draw tracer curve. The method is defined as a way in which a pigment flow is carried out to influent and then, when the pigment reaches effluent, pigment concentration is measured. Following which, three steps are regarded to draw curve tracer comprised of solving the flow equation steadily in ANYSY Solver, defining pigment in pre-CFXANSYS and then checking pigment concentrations in influent and effluent after 3 hours. It should be added that hydrodynamic conditions are expressed in terms of three laws in which conservation of mass, conservation of momentum (Newton's Second Law) and conservation of Energy (the first law of thermodynamics) are considered.

3 Tracer curve method Evaluation

Maximum time of flow discharge in the current study will be compared with Garcia outcomes in the same aspect to draw an evaluation (Garcia, 2011). Figure 4 shows the comparison between these two studies in the sense of tracer curves. Table 1 also shows maximum time of tracer curves where tank depths are taken of 12 feet depth and two different baffle height of 7 and 5 feet to compare with Garcia's studies reports.

Table 2.

Fig 4.

As it is observed, data dispersion (current study) is in a good agreement with Garcia study in which trend lines are going up by 45^0 slope. Beside this, standard deviations of both A and B graphs are close to 1. Therefore, modeling of Chicago tank by tracer curve is effective and accurate enough to predict other basin tank depths and baffle heights.

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4 Result and discussion

4.1 The effect of tank depth variation

The tracer curves evaluate the tank performance where the tank depth (D_t) and the baffle height (D_f) change within pigment injection for 5 seconds. Then, the pigment concentrations will be measured in the inlet and outlet (effluent) over three hours to find the difference in between. Figures 5 and 6 display the tracer curves results for the tank depth variation and baffle height of 1.52 and 2.13 meter in which the tank diameter is equal to 47.24 meter.

Fig 5.

According to Fig 5, as tank depth increases, it takes more time (t_{max}) to discharge effluent. Therefore, Hydraulic Retention Time (HRT) will rise slightly that is more evident in peak points' locations. It is clear from the data given that 0.34 hr time elapse is observed from 3.66 (1.19 hr) to 1.52 m (1.53 hr) depths peak points distance. Moreover, the higher tank depth is, the gaps among peak points are getting thinner. Particularly, the gap between 4.57 and 1.22 m tank depths is narrower compared with the gap between 3.66 and 3.96 m or even though for the tank depths of 3.96 and 4.27 m are. If the tank depth is more than 4.57 m the gap will not be noticed. Thus, tank depths which are more than 4.57 m, are not economically beneficial because there would not be excessive time discharge for the tank and this imposes more cost to construction of bigger scale tanks which is not effective on the effluent concentration showing on the vertical axe.

Furthermore, the points (t_0) where the lines start to have more effluent concentration and tank is getting filled with pollutions are different. To illustrate that, tank depths of 3.66 and 4.57m starting points are 0.64 and 0.91hr, respectively. Therefore, deeper tanks get polluted lately. Comparing the maximum points' effluent concentration indicates that C_{out}/C_o ratio falls markedly from 3.66 to 4.57m tank depths given that the optimum tank depth is 4.57m; however, there is not significant gap between 4.27 and 4.57m depths.

Fig 6.

Fig 6 (baffle height of 2.13 ft) also shows the similar manner as it is observed in Fig 5. Although, t_{max} is slightly less than what it is in Fig 5. Plus, the effluent concentrations (C_{out}/C_o ratio) are quite equal in all tank depths with a bit drop from tank depths of 3.66 to 4.57 m. Also, the same behavior holds for t_0 as it is discussed previously.

Overall, there is no significant difference between tank baffle of 1.52 and 2.13m. However, tank baffle of 5m can provide more HRT or discharge time by the calculation of tracer curves in same properties.

4.2 The effect of tank diameter variation

Tank diameter can change t_{max} and following that the effluent concentration may vary. In this regard, diameter variation effect on these parameters is analyzed in this part. As it is showed that tank baffle of 1.52m gives less effluent concentration, it is selected for the following comparison. Fig 7 and 8 display tank performance in 42.67 and 51.8m diameter in which tank depths are 3.66, 3.96, 4.27 and 4.57m, respectively.

Fig 7.

Fig 8.

Fig 7 and 8 show that t_{max} changes considerably where the diameter extends from 42.67 to 51.82m, t_{max} has noticeably risen. That is more evident in tank depths of 4.57m in two figures in which t_{max} is 1.41 and 1.63hr in 42.67 and 51.82m diameters, respectively. Plus, there is still gaps among lines which are getting narrower as higher tank depths take place.

5 Conclusion

In this study, tracer curve is used to analyze settling tank performance in which the given tank is firstly evaluated with previous study. The results of evaluation were homogenized with the study and similar outcomes were hand in. Then, the effect of tank depth variation, baffle height and tank diameter were investigated in which higher tank depth increases the discharge time. Also, where the tank depth is higher, the effluent concentration is lower. Comparing baffle heights of 1.52 and 2.13m showed that the discharge time is wide where baffle height of 5ft. Therefore, smaller baffle heights are effective to delay the time of effluent discharging. Tank diameter variation analysis indicated that larger tank diameter give in more time to discharge which is evident in tank depth of 51.82m comparing to 45.72m. The time which tank is getting polluted and the effluent is concentrated, also depends on tank depth and diameter. That is more when the tank depth and diameter are considered in larger sizes.

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Table 1. Properties of settling tank

Parameters	Unit	Dimension
Tank diameter	(m)	47.24
Baffle diameter	(m)	12.8
Tank depth	(m)	3.66
Baffle height	(m)	1.52
Inlet pipe diameter	(m)	1.37
Bottom Slope	-	1:12

Table 2. Tracer curve outcome for two aforementioned studies

Tank depth (m)	Baffle Height (m)	Time of discharge (hours) (current study)	Time of discharge (hours) (Garcia, 2011)
0.3	0.127	1.19	1.22
0.3	0.18	1.14	1.25

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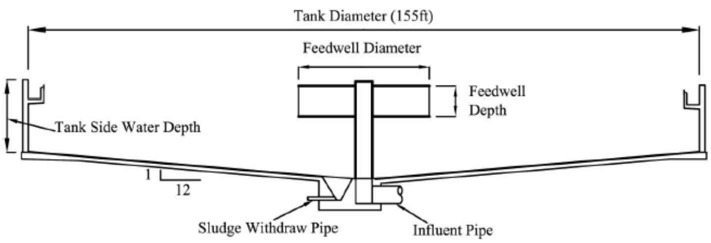

Fig 1. Chicago tank.

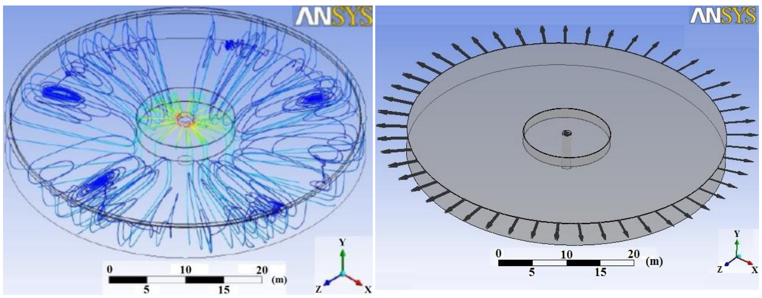

Fig 2. Flow lines and directions in the settling tank.

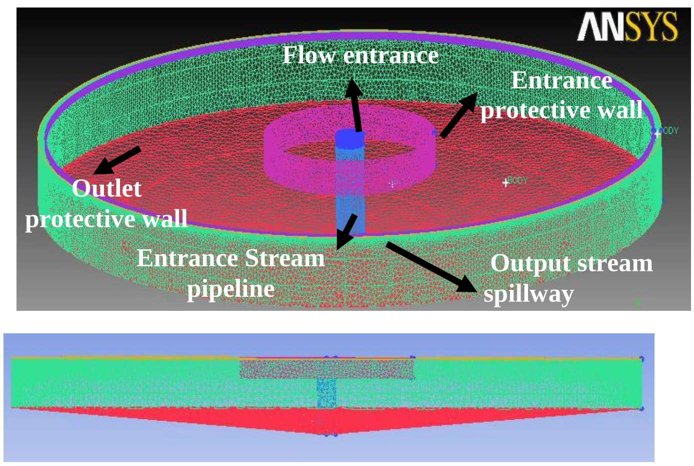

Fig 3. Modelled settling tank.

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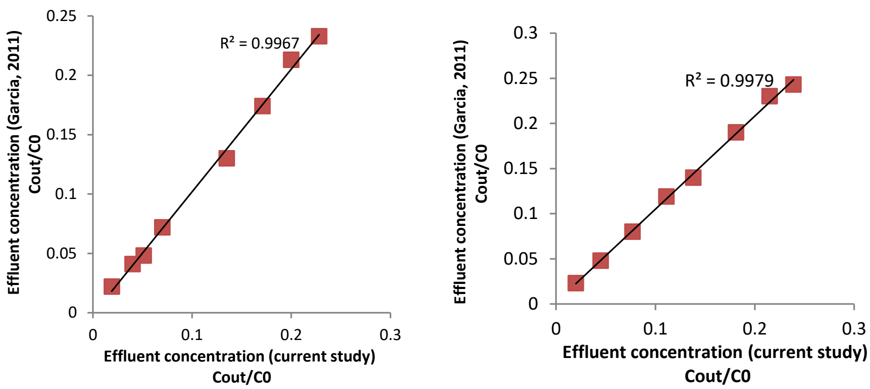

A. baffle height of 5m B. baffle height of 7m

Fig 4. Data dispersion in current and Garcia' studies (2011).

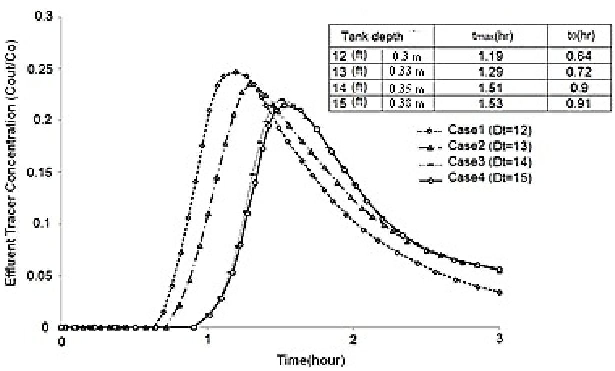

Fig 5. Effluent concentration with baffle height of 5 feet in tank depths variation.

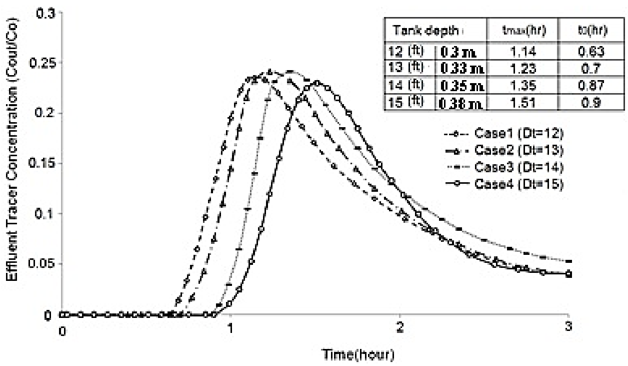

Fig 6. Effluent concentration with baffle height of 7 ft in tank depths variation.

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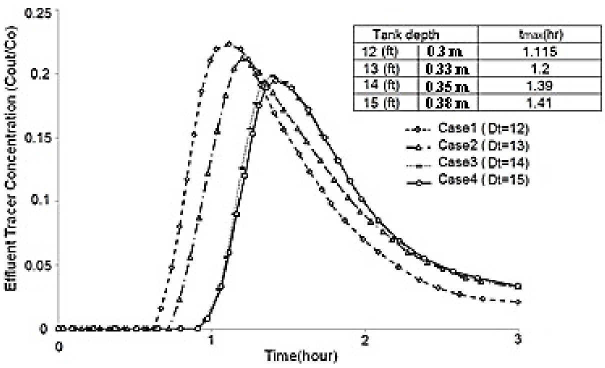

Fig 7. Effluent concentration and tmax in tank depths variation and 140 feet diameter.

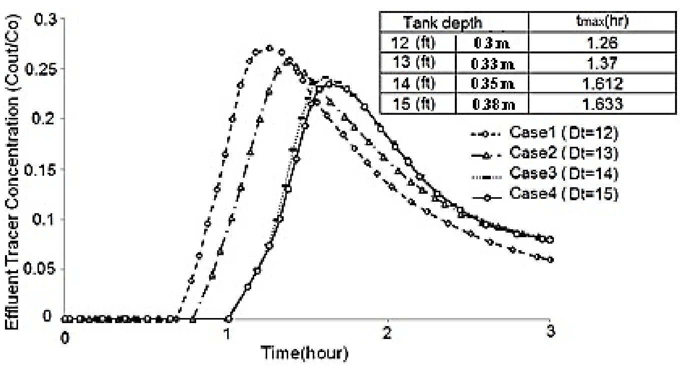

Fig 8. Effluent concentration and tmax in tank depths variation and 170 feet diameter.