doi: 10.2965/jwet.19-052 Journal of Water and Environment Technology, Vol.17, No.6: 420–431, 2019

Original Article

Improvement of Suspended Solids Removal Efficiency in Sedimentation Tanks by Increasing Settling Area Using Computational Fluid Dynamics

The-Anh Nguyen [a,b], Nguyet Thi-Minh Dao [a,c], Mitsuharu Terashima [a], Hidenari Yasui [a]

[a] *Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyusyu, Japan*
[b] *Faculty of Water Resources Engineering, Thuy Loi University, Hanoi, Vietnam*
[c] *Department of Environmental Engineering, National University of Civil Engineering, Hanoi, Vietnam*

ABSTRACT

In the renovation design of sedimentation tanks for the wastewater treatment plant, the small settling velocity particles should be removed to improve total suspended solids (SS) removal efficiency. Theoretically speaking, when the flow rate is constant, the increased settling area in the sedimentation tank results in high removal efficiency of small settling velocity particles. Alternatively, the SS removal efficiency increases in lamella settling tank as installing inclined plates. However, the actual effect of increased settling area due to different tank configuration to improve the removal efficiency of small settling velocity particles was not fully investigated. In this study, the computational fluid dynamics model was applied to simulate the effect of increased settling area on SS removal efficiency in three types of configuration when flow rate was remained unchanged. The simulation results show that the highest SS removal efficiency was observed in the tank with increased settling area by extending the length of the tank, in which the increased settling area contributed 69% to improve the removal efficiency of small settling velocity particles. These results have an important role in optimizing the design to enhance the SS removal efficiency of the settling tank.

Keywords: increased settling area, small settling velocity particle, computational fluid dynamics

INTRODUCTION

The sedimentation tank plays an important role in water and wastewater treatment systems by settling suspended particles using gravity. The effective performance of the settling tank contributes largely to the reduction of suspended solids (SS) which is an importance parameter in wastewater quality index. However, the low settling velocity (*SV*) desired in the settling tank requires a large surface area, which might be difficult in restricted areas.

An effective way to increase the settling tanks' performance is to introduce inclined plates to increase the settling area and improve the hydraulic regime. Extensive research on the performance and optimization of inclined plates, as well as the mechanism of the sedimentation process in lamella settlers were carried out. Demir [1] investigated the optimum angle of the baffle in the lamellar settling tank at various linear velocities. Kowalski [2] compared the SS removal efficiency in the conventional tank and the lamella settling tank taking into account the density, viscosity, and mass fraction of solid particles. Different types of tube settlers were examined by Fujisaki and Terashi [3] to obtain a higher solid separation capacity. Leung [4] studied the distribution of three-layer, stratified viscous channel flow between inclined plates. The above-mentioned studies successfully predicted the SS removal efficiency in lamella settling tanks.

Theoretically speaking, in the design of lamella settlers, a large assumption was made on the effectiveness of baffles, in which the entire horizontal projected area of inclined plates was considered to be involved in increasing the settling area

Corresponding author: Mitsuharu Terashima, E-mail: m-terashima@kitakyu-u.ac.jp
Received: June 12, 2019, Accepted: September 2, 2019, Published online: December 10, 2019

in lamella settling tanks. Moreover, SS removal efficiency was assumed to be constant if the increase and/or decrease of settling area and flow rate were proportional [5,6] because other factors such as vortex and density current have been considered as non-impacting ones. However, in practical operation of lamella settlers, such factors should be taken into account as contributors to the SS removal efficiency. In experimental conditions, it is a big challenge to evaluate all factors affecting the settling process that is the reason why the application of simulation is essential in the evaluation of whole process.

Many studies have focused on the hydraulic regime in the settling tank. For example, in 1989, Stamou *et al.* [7] used a numerical model to study the flow and settling process of SS in primary sedimentation tanks, and compared the simulation results to those from the theoretical method. Goula *et al.* [8] evaluated the impacts of baffles in the inlet zone on the distribution of flow pattern, and the influence of SS mass fraction on their removal efficiency.

The application of computational fluid dynamics (CFD) to simulate the settling process has been widely accepted due to its visualization capabilities and data on the hydraulic regime under different conditions of geometry and flow pattern, density and vortex zone, mass fraction and settling velocity of particles. Asgharzadeh *et al.* [9] and Shahrokhi *et al.* [10] investigated the reduction of dead zones and recirculation zones in cases where a different number of baffles was installed at the bottom of the tank. Similarly, Heydari *et al.* [11] conducted simulations on the angle of the baffle at the bottom of the settling tank to reduce the vortex zone. Ghawi and Kriš [12] developed a complex CFD model to estimate the factors that impact deposition efficiency. Tarpagkou and Pantokratoras [13] proved that inclined plates improved the hydraulic regime by simulating a full-scale system, rather than a part of the system as in previous research. Nguyen *et al.* [14] assessed the influence of inclined plates on attainable flow rate of lamella settling tank, in which particle group with a removal efficiency of 89% in original settling tank was selected to calculate the effectiveness of inclined plates (α). The results showed that the effectiveness of inclined plates to attainable flow rate was significantly lower than the theoretical value.

In this study, the CFD model is applied to simulate the effect of an increased settling area to improve the total SS removal efficiency in sedimentation tanks. The research was carried out with several tank configurations and various groups of particle. The research results help the designer to have a solution to improving performance in sedimentation tanks.

MATERIALS AND METHODS

Numerical modelling methods

The Eulerian-Eulerian approach which provided conservation equations for mass and momentum was adopted to simulate the multiphase-flow of liquids and solids. The Algebraic Slip Model was selected for simulation of the velocity profile and the concentration distribution of SS. Each dispersed component is represented by a mass fraction equation and a relative movement is allowed between these components in the continuous phase [15]. Turbulence in the liquid phase was modelled using the K-epsilon model, which successfully simulated the sedimentation tank in previous studies [16]. The hydrodynamic and flow behavior in the sedimentation tanks were modelled in two dimensions. In this study, the commercial software CFX 18.0 (in ANSYS) was used to perform CFD modelling. The hexahedral meshes were generated by ANSYS meshing for numerical calculations.

Model validation

Validation of the model was conducted by comparing the simulation results and the experimental data on flow and settling pattern in sedimentation tanks studied by Stamou *et al.* [7]. Using their configuration and the settling velocity curve of SS, a rectangular settling tank was simulated at 3 linear velocities (*LV*) of 37, 60 and 110 m/d. A good agreement between model simulation and experimental results was observed (**Fig. 1**). As a result, the proposed model was suited for modelling the settling process in sedimentation tanks.

Model geometry

The study was conducted with three types of configuration:

In the first type of configuration: The settling tank size is maintained ($H \times W \times L = 2 \times 0.02 \times 4$ m) with the increased settling area by increasing the number of inclined plates in the tank. The number of 4, 8 and 16 inclined plates of the same configuration were installed at a 60° angle, which was widely applied in lamella settler design to obtain self-cleaning and high removal efficiency [6], in tanks B, C, and D respectively; longitudinal depth of 0.5 m; and spacing of 0.8, 0.4, and 0.2 m, respectively. Print tank E, 16 baffles at a longitudinal depth of 1 m were introduced at 0.2 m apart.

In the second type of configuration: The width and height of the tank remain the same with original settling tank A ($H \times W = 2 \times 0.02$ m), the settling area is increased by increas-

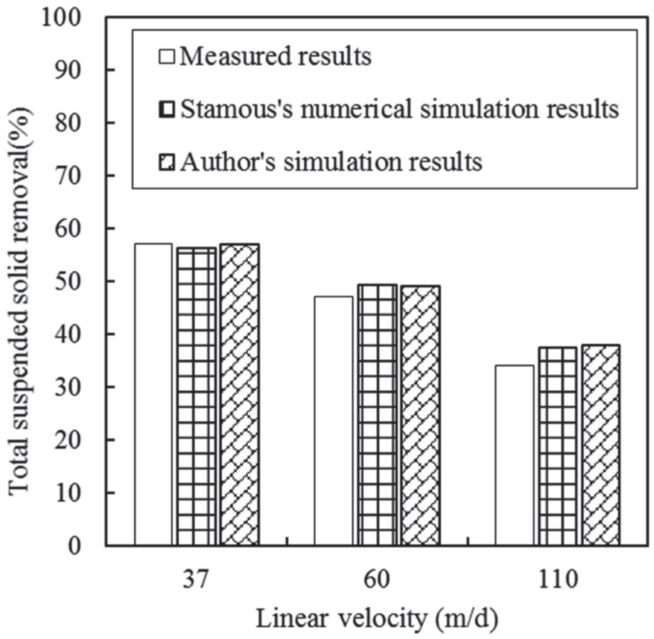

Fig. 1 Comparison of measured and simulated results.

ing the length (L) of the tank from 4 to 7.5, 11, 18, and 32 m in tanks F, G, H and I, respectively.

In the third type of configuration: The tank size was the same as in the settling tank A ($H \times W \times L = 2 \times 0.02 \times 4$ m), the settling area is increased by raising the number of tanks from 1 to 8 tanks, which corresponded to the settling area (δ) increased from 0 to 7. The flow rate into each tank was decreased from 1 to 8 times. The CFD modeling of this configuration was equivalent to the simulation of a settling tank with the width (W) increased.

Here, a different configuration was used, as shown in **Figs. 2 and 3.**

Boundary condition

In sedimentation tank design, the LV commonly selected is between 1 and 2 $m^3/(m^2 \cdot h)$ [17]. Therefore, in this study, a primary sedimentation unit located in the wastewater treatment process was simulated under original LV of 1 $m^3/(m^2 \cdot h)$, inlet 200 mg-SS/L, water density 998 kg/m^3 and particle density of 1020 kg/m^3.

In the model, the mass flow rate was selected at both the inlet and outlet. No slip wall was set for the bottom, the wall or the baffles. The water-surface was best defined by VOF method in some studies [18,19], in case of simulating the complicated surface between two fluids (air and water). In this study, the surface was almost flat and simple, so the free slip wall was selected to setup the surface boundary condition. The water surface was assumed to be horizontal in the tank, which was also widely applied for simulation of settling tank in previous research [13,20,21]. The particles were set to be deposited only at the bottom; not on the wall or baffles.

The transient-type simulations were selected in this study. The initial time step was set at 5 seconds for the adaptive option in all calculations. For the numerical method, the advection scheme was upwind and the transient scheme was set as second-order backward Euler.

Selection of appropriate mesh size

In order to check the mesh sensitivity, different mesh sizes ranging from 5-80 mm, corresponding to 324,538 and 1,857 number of elements, were used to simulate SS removal efficiency in lamella D (δ = 3.46). By enlarging the mesh size, SS removal efficiency decreased from 87% to 81% according to the results. At mesh sizes of 5, 10 and 20 mm, SS removal efficiencies were similar. Consequently, the 20 mm-mesh size was selected for conducting subsequent simulations, assuring to provide accurate results and reasonable simulation time.

Selection of appropriate groups of particles

In the CFD model, SS particles in the influent were grouped and represented by average settling velocities for simplification in **Table 1**. To verify the sensitivity of group numbers, the simulation of SS removal efficiency of lamella D (δ = 3.46) was conducted using different particle groups ranging from 1 to 20. By increasing particle groups, the SS removal efficiencies decreased from 97 to 87%. The groups from 10 to 20 provided results without much difference. Hence, 10 groups of particles were used for the following simulations.

Calculation of SS removal efficiency from simulation results

The SS removal efficiency for each group of particles was calculated as:

$$\eta_i = \frac{C_{in}^i - C_{out}^i}{C_{in}^i} \qquad (1)$$

where

- η_i : SS removal efficiency of particle group i (from 0 to 1)

- C_{in}^i : concentration of particle group i (from 1 to 10) at the inlet (mg/L)

- C_{out}^i : concentration of particle group i (from 1 to 10) at the

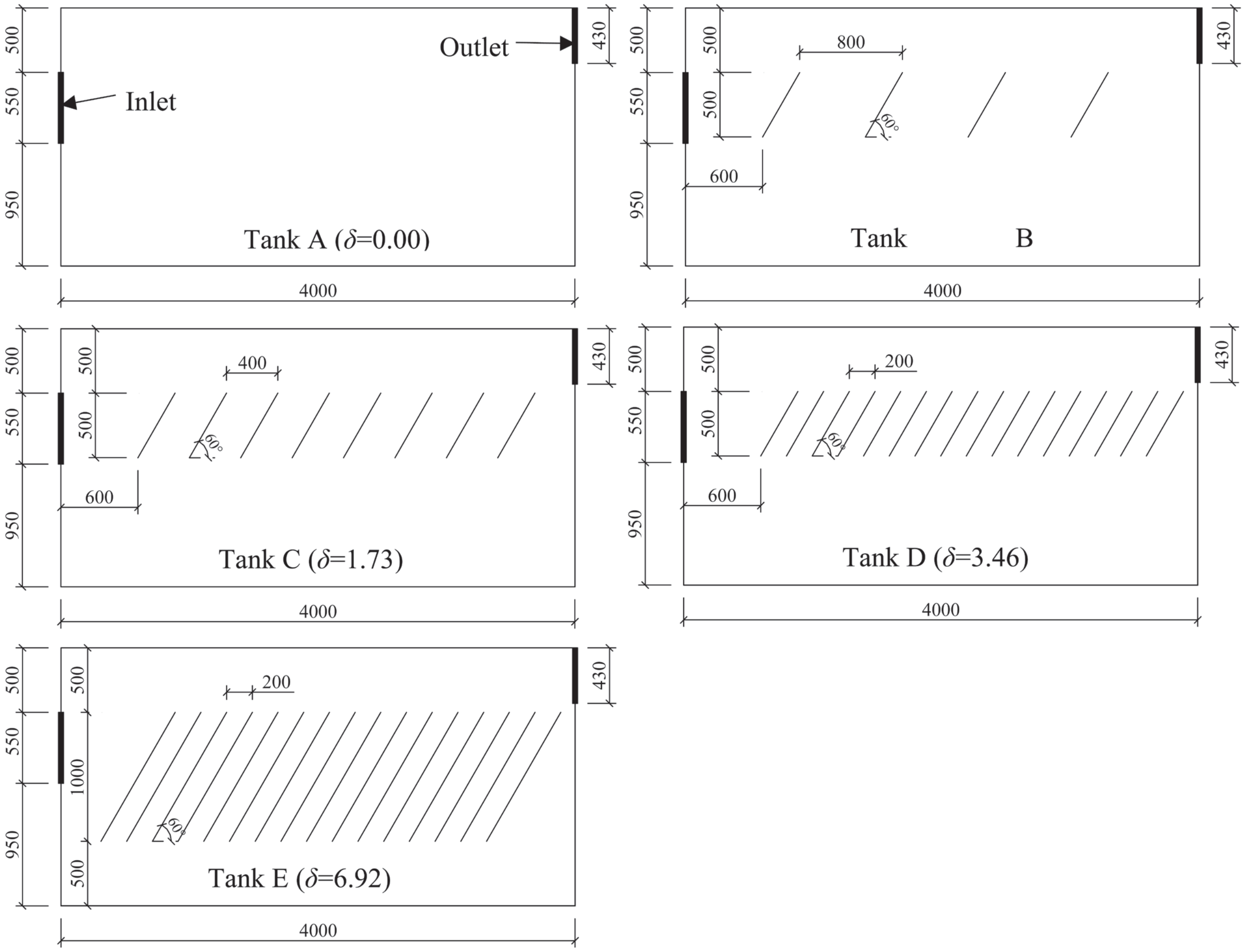

Fig. 2 Cross section of settling tank and lamella settling tanks.

outlet (mg/L)

The settling area in a settling tank

$$A = A_o + A_\delta \tag{2}$$

$$A_\delta = A_b \text{ or } A_L \text{ or } A_W \tag{3}$$

where

- A: total settling area in the settling tank (m^2)
- A_o: surface area in the original settling tank ($W \times L = 0.02 \times 4 = 0.08$ m^2)
- A_δ: increased settling area by installing inclined plates or increasing the length of the tanks or increasing the width of the tanks as shown in **Fig. 4**
- A_b: horizontal projection area of the inclined plate ($A_b = n \times W_b \times L_p$) ($m^2$)
- A_L: increased surface area by increasing the length of the tank ($A_L = L_\delta \times W$) (m^2)
- A_W: increased surface area by increasing the width of the tank ($A_W = L \times W_\delta$) (m^2)

where - n: number of inclined plates in lamella settling tank

- W: width of the original settling tank (m)
- W_b: width of the inclined plate (m)
- W_δ: increased width of the tank (m)
- L: length of the original settling tank (m)
- L_p: horizontal projection length of the inclined plate ($L_p = L_b \times \cos 60°$) (m)
- L_b: length of the inclined plate (m)
- L_δ: increased length of the tank (m)

The ratio of increased settling area was:

$$\delta = \frac{A_\delta}{A_o} \tag{4}$$

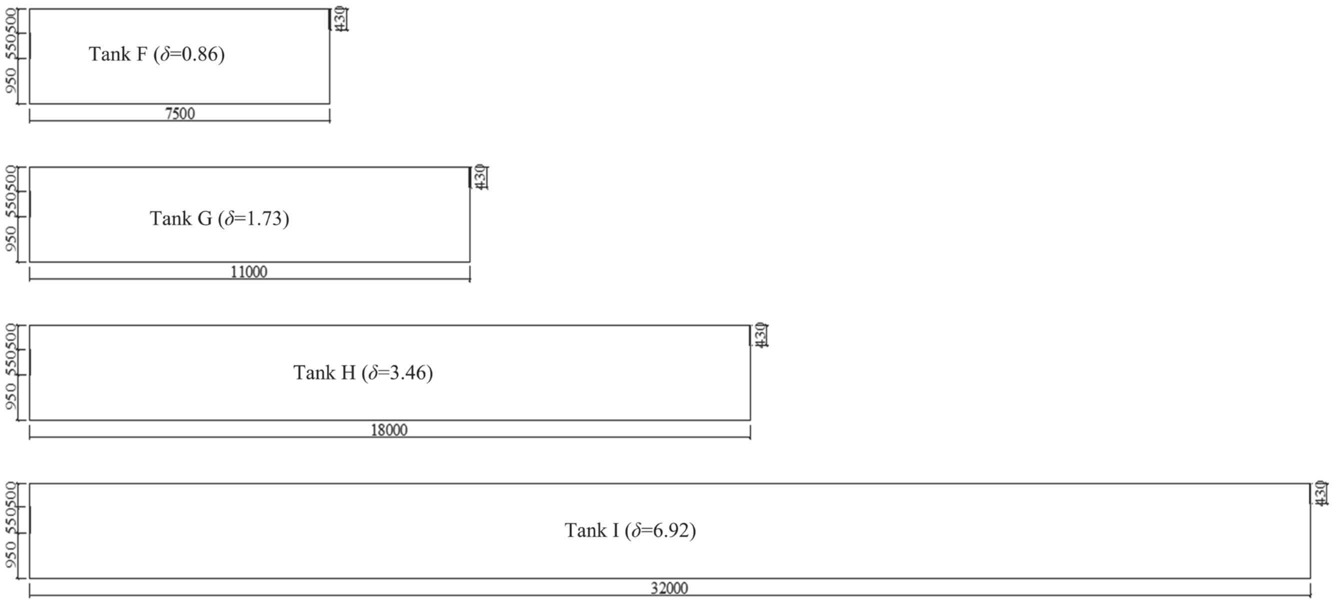

Fig. 3 Cross section of settling tanks.

Table 1 Settling velocities for group number sensitivity test.

1 group	Particle group No.	1
	Settling velocity (m/h)	1.88
	Mass fraction	1.00

2 groups	Particle group No.	1	2
	Settling velocity (m/h)	1.38	2.38
	Mass fraction	0.50	0.50

5 groups	Particle group No.	1	2	3	4	5
	Settling velocity (m/h)	0.88	1.38	1.88	2.38	2.88
	Mass fraction	0.20	0.20	0.20	0.20	0.20

10 groups	Particle group No.	1	2	3	4	5	6	7	8	9	10
	Settling velocity (m/h)	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
	Mass fraction	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

20 groups	Particle group No.	1	2	3	4	5	6	7	8	9	10
	Settling velocity (m/h)	0.69	0.81	0.94	1.06	1.19	1.31	1.44	1.56	1.69	1.81
	Mass fraction	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Particle group No.	11	12	13	14	15	16	17	18	19	20
	Settling velocity (m/h)	1.94	2.06	2.19	2.31	2.44	2.56	2.69	2.81	2.94	3.06
	Mass fraction	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

where

-δ: increased settling area

Definition and calculation of the effectiveness of increased settling area related to ratio SV_{90}/LV_o (ψ_{90})

According to the theory of sedimentation [5,6], LV in the sedimentation tank is calculated as:

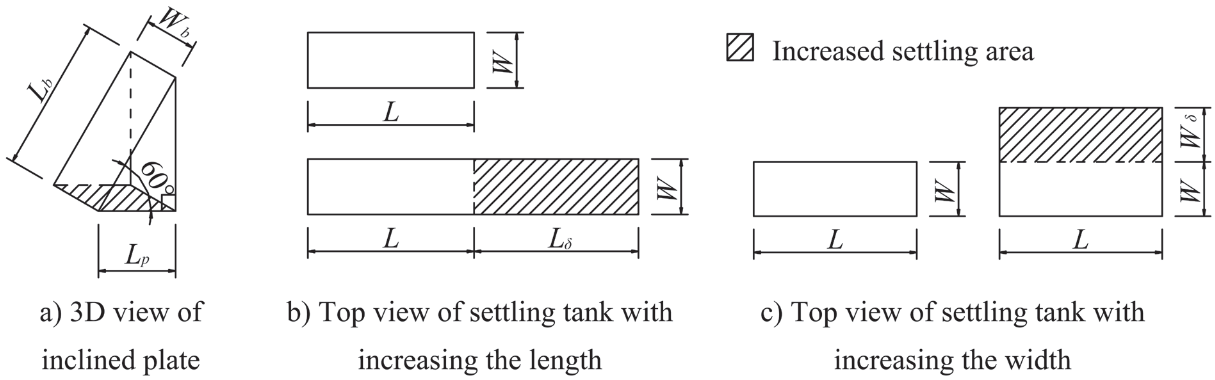

Fig. 4 The increased settling area of settling tank and lamella settling tanks.

$$LV_o = \frac{Q_o}{A_o} \tag{5}$$

Similarly, LV in the lamella settling tank and settling tank when increased δ was ideally calculated as:

$$LV_i = \frac{Q_o}{A_o + A_\delta} \tag{6}$$

Ideally, it is assumed that when ratio SV_i/LV_i is constant, the η of particle group will be unchanged. When 90% removal efficiency was considered [14], the settling velocity, with which the particle had the η of 90%, in original settling tank was defined as $SV_{90\text{-}o}$.

$$\frac{SV_{90-o}}{LV_o} = \frac{SV_{90-i}}{LV_i} \tag{7}$$

or

$$SV_{90-i} = \frac{A_o \times SV_{90-o}}{A_o + A_\delta} = \frac{SV_{90-o}}{1+\dfrac{A_\delta}{A_o}} = \frac{SV_{90-o}}{1+\delta} \tag{8}$$

A coefficient for the effectiveness of increased settling area (β) reflects the actual effect of the increased settling area by improving the η of small SV particle groups. The value of β = 1 indicated that the entire increased settling area contributed to increasing the η of the particle group. On the other hand, the value of β=0 indicated that there was no impact from increased settling area, as shown in equation 9.

Equation 8 should be:

$$SV^*_{90-i} = \frac{SV_{90-o}}{1+\beta\times\delta} \tag{9}$$

where

- LV_o: linear velocity in the original settling tank (m^3/(m^2·h))
- LV_i: linear velocity in the improved settling tank (m^3/(m^2·h))
- Q_o: flow rate in the original settling tank (m^3/h)
- $SV_{90\text{-}i}$: ideal settling velocity of particle group i in improved tank which had the η of 90% (m/h)
- $SV^*_{90\text{-}i}$: actual settling velocity of particle group i in improved tank which had the η of 90% (m/h)
- β: effectiveness of increased δ to improve the η of small SV particle groups (from 0 to 1).

In this study, particle group with η of 90% in original settling tank was selected to calculate the effect of δ on improving η of small SV particle groups by ratio $\psi_{90\text{-}i}$, which was the ratio between $SV_{90\text{-}i}$ in improved tank and LV_o.

$$\text{In ideal condition: } \psi_{90-i} = \frac{SV_{90-i}}{LV_o} \tag{10}$$

$$\text{In actual condition: } \psi^*_{90-i} = \frac{SV^*_{90-i}}{LV_o} \tag{11}$$

The relationship between ψ^*_{90-i} and δ was calculated:

$$\psi^*_{90-i} = \frac{SV^*_{90-i}}{LV_o} = \frac{SV_{90-o}}{(1+\beta\times\delta)\times LV_o} = \frac{\psi_{90-o}}{1+\beta\times\delta} \tag{12}$$

where

- $\psi_{90\text{-}o}$: the ratio between $SV_{90\text{-}o}$ and LV_o.

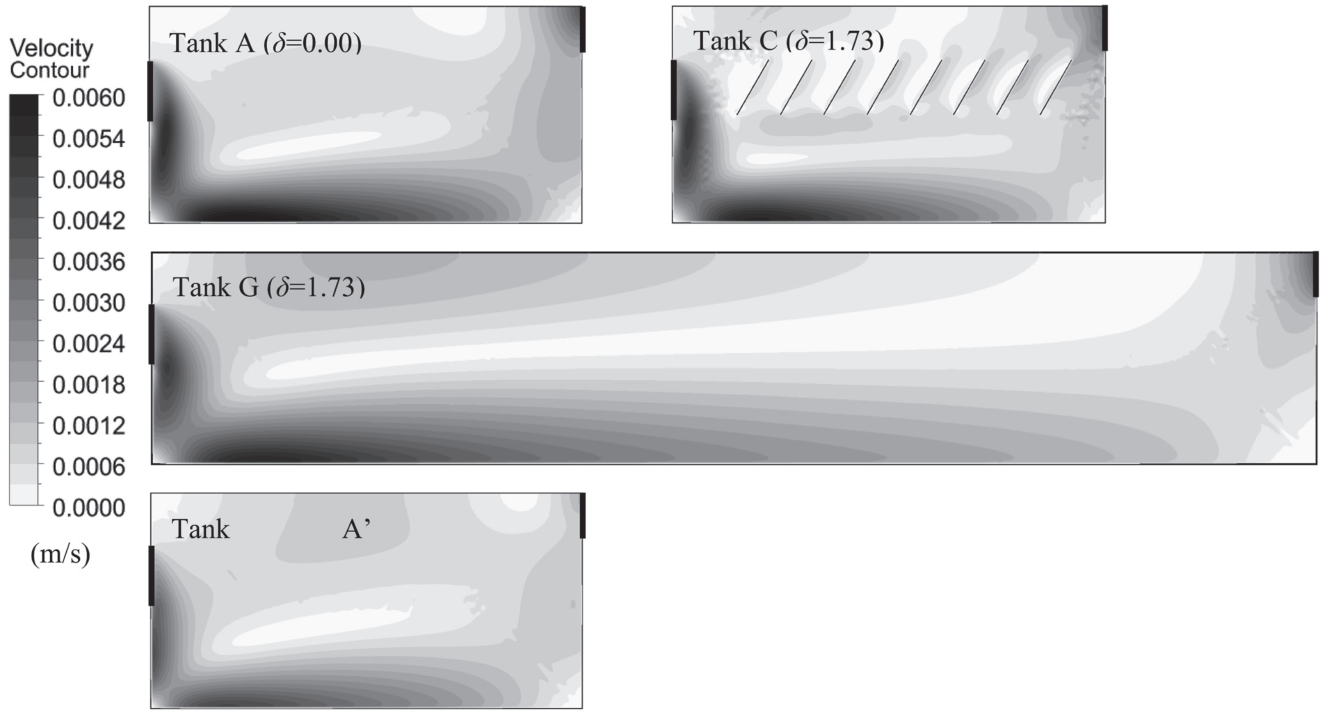

Fig. 5 Contour of velocity for settling tanks and lamella settling tanks.

RESULTS AND DISCUSSION

Relationship between SS removal efficiency (η) and increased settling area (δ)

The contour plots of velocity in the modelled tanks with δ = 0 and δ = 1.73 are shown in **Fig. 5**. In tank C, the small velocity zone (with white colour) appeared in the middle of the inclined plates, resulting in easier settling of particles on the surface of inclined plates. This results indicated that the settling process was improved by inclined plates in tank C. In tank G, the small velocity zone was seen extending from the inlet to the outlet. The small velocity zone helps stabilize the settling process in the tank, thus improves particles removal efficiency. Moreover, the velocity near the outlet was seen lower compared to in tank A, which was also the reason for increasing the SS removal efficiency in this tank. In tank A', which had the same size as tank A, the flow rate into the tank decreased by 2.73 times compared to in tank A, so the velocity in the whole tank was lower than the one in tank A. Hence, the performance of particles removal was increased.

Figures 6, 7, and 8 show the relationship between the increased settling area and the SS removal efficiency in the sedimentation tank.

The simulation results of SS removal efficiency in lamella settling tanks in **Fig. 6** indicated that the more inclined plates installed (increased δ), the better the SS removal efficiency achieved for each particle group (η_i). For particle groups with small settling velocities (particle group 1, SV = 0.75 m/h), inclined plates were thought to have little impact on SS removal efficiency. At a constant flow rate, as δ increased from 0 to 6.92, the largest improvement on η was observed for particle groups 3 to 7 (SV = 1.25 to 2.25 m/h), at values of 12 and 8%. For particle groups 8 to 10 (SV = 2.50 to 3.00 m/h), no significant enhancement of SS removal efficiency was achieved due to the high inherent settling capacity of these particles.

As shown in **Fig. 7**, the η increased significantly in almost particle group as increasing the δ. With δ increasing from 0 to 6.92, there was a sharp increase in η for particles groups 1 to 7 (SV = 0.75 to 2.25 m/h) with 49 to 8% respectively. The high η was recorded in particle groups 8 to 10 (SV = 2.50 to 3.00 m/h) in the original settling tank, so η only increased by 6 to 3% corresponding to these particle groups. Especially at δ = 6.92, all particle groups were completely removed in the sedimentation tank.

According to the simulation results in **Fig. 8**, the η was observed to increase gradually for each particle groups. For particle groups 1 to 7 (SV = 0.75 to 2.25 m/h), the improvement of η increased with 33 to 8% respectively. For particle groups 8 and 10 (SV = 2.50 to 3.00 m/h), the improvement

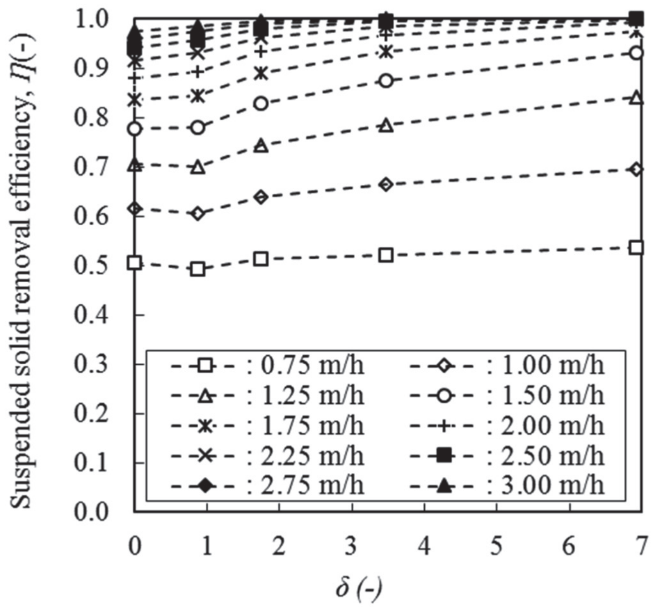

Fig. 6 Relationship between η and δ for increased δ by installing inclined plates.

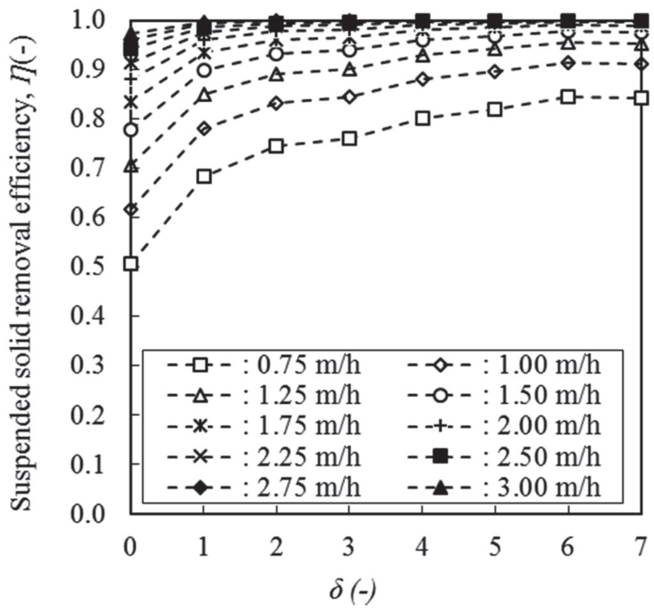

Fig. 8 Relationship between η and δ for increased δ by increasing the width of the tank.

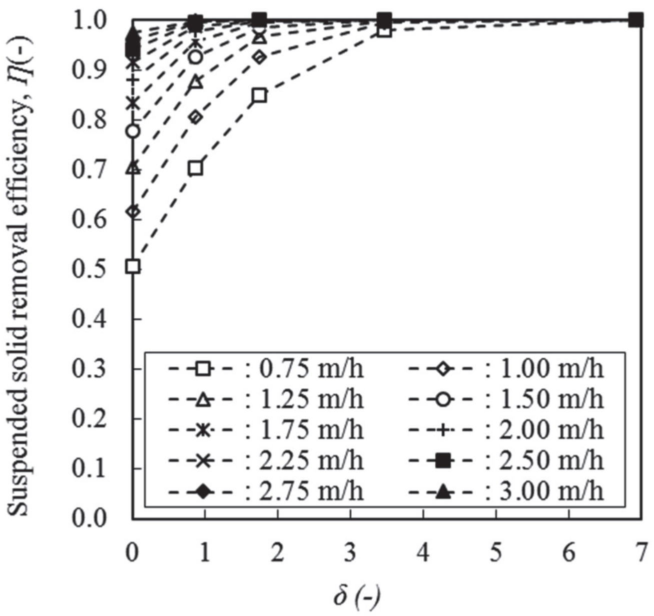

Fig. 7 Relationship between η and δ for increased δ by increasing the length of the tank.

of SS removal efficiency was similar to two cases aforesaid.

Therefore, when the flow rate was constant, the increasing δ leads to enhance the removal efficiency of each particle group. With the same δ, the highest SS removal efficiency was observed in settling tanks with increased δ by increasing the length. In contrast, when the δ was increased by installing inclined plates, the SS removal efficiency was obtained the lowest value. For each particle groups, the higher improvement of η was recorded in small *SV* particle groups, rather than the large one.

Effectiveness of δ to improve the η of small *SV* particle groups

To assess the effect of δ on removal efficiency of small *SV* particle groups, in this study, the particle group with a η of 90% corresponding to $SV_{90\text{-}o}$ = 2.14 m/h and $\psi_{90\text{-}o}$ = 2.14 in the original settling tank was selected. Based on the results in **Figs. 6, 7, and 8**, the ψ_{90} is calculated for other particle groups with the same η of 90% when the δ increased.

From the results in **Figs. 6, 7 and 8,** the horizontal line η =0.90 was plotted and intersections with the other linear curves represented different values of *SV* corresponding to an increased δ. Then, the relationship between ψ_{90} and increased δ was plotted in **Fig. 9**. When δ increased, leads to a decrease in the ψ_{90}, which means that the increased δ enhance removal efficiency in small *SV* particle groups. For example, in ideal condition, when δ increased to 1, the ψ_{90} should decrease from 2.14 to 1.07 (2 times reduction) for all three cases. However**,** the ψ_{90} only decreased from 2.14 to 1.98, 1.73, and 1.26 corresponding to increased δ by installing inclined plates, increasing the length, and increasing the width, respectively. Thus, the removal efficiency of small *SV* particle group with ψ_{90} in case 2 was the best performance,

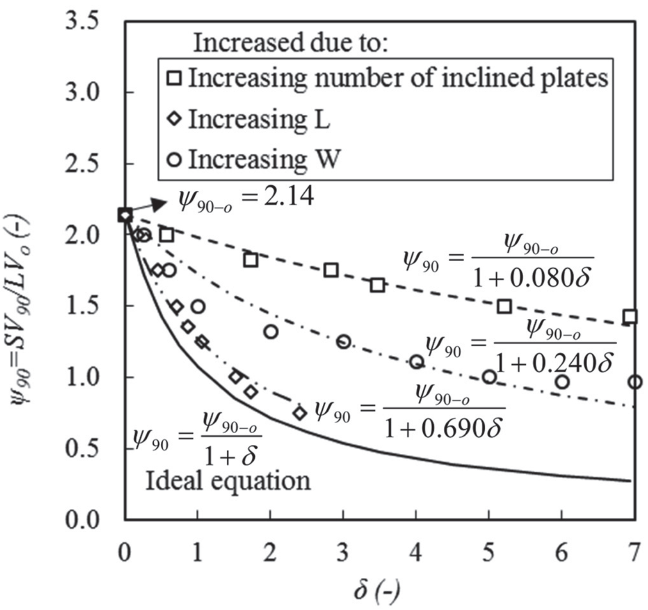

Fig. 9 Relationship between ψ_{90} and δ at $\eta = 0.90$.

the particle group with SV_{90} of 1.26 m/h was removed with η= 90% compared to the particle group with $SV_{90\text{-}o}$ of 2.14 m/h.

As the results in **Fig. 9**, the coefficient β increased from 0.08 (increased δ by inclined plates) to 0.24 (increased δ by increasing the width) and 0.69 (increased δ by increasing the length), the results indicated that the increased δ by increasing the length was contributed the highest performance to small SV particle groups with a coefficient β of 0.69. However, this value was still smaller than the ideal value of $\beta = 1$.

In the previous study, Nguyen *et al.* [14] investigated the effect of increased δ by installing inclined plates to increase the attainable flow rate of the settling tank (α). The research results showed that the increased δ due to installing inclined plates only contributed 12.56% to increase the attainable flow rate. In this study, the effectiveness of the increased δ to the removal efficiency of small SV particle groups (β) was 8.0%, which was an insignificant difference compared to the α value. These findings revealed the actual contribution of inclined plates of about 10% to improve the η of small SV particle groups and increase the attainable flow rate, which was significantly lower than ideal calculation value.

Improvement on the hydraulic regime in settling tanks and lamella settling tanks

In some studies [22,23], a baffle plate was used to orient the inlet flow to the bottom of the settling tank. However, as illustrated by the simulation, even without the baffle plate, the difference between SS density and water temperature still created a downward flow, known as the density current [12,24], as shown in **Fig. 10**.

In order to clearly understand the effect of the hydraulic regime on the SS removal efficiency, the Y-direction velocity was compared between δ of 1 (in the original settling tank) and 1.73 (in three cases) at a depth of 1 m.

Theoretically speaking, when δ increases to 1.73 cor-

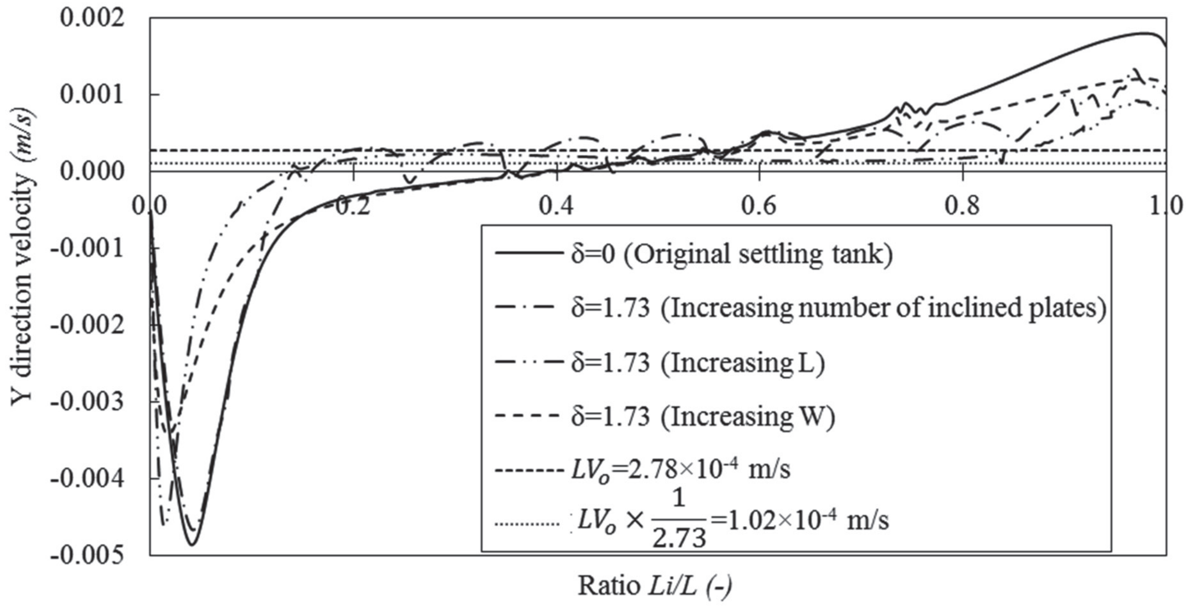

Fig. 10 Y direction velocity at $H = 1$ m, $\delta = 1$ and 1.73.

a) Top view of settling tank with increasing the width

b) Top view of settling tank with increasing the length

Fig 11 Arrangement of settling tank layout.

responding to a decrease in *LV* with the same ratio, so the small *SV* particle group with *SV* higher than the decreased *LV* could be removed. The results in **Fig. 10** indicated that the Y-direction velocity was different between other tanks with the same increased δ. In the case of increasing δ by installing the inclined plates, the velocity fluctuated in the middle of the tank. Nevertheless, the velocity near by the outlet zone was smaller than the one in the original settling tank. This result suggested that the η should be increased thank to improving the hydraulic regime by installing inclined plates. In the tank with increased δ by increasing the width, the velocity was almost unchanged from inlet to the middle of the tank compared to the original settling tank, the velocity near the outlet zone slightly decreased, led to increase η for small particle groups. Especially, in tank with increasing length, the velocity was stable and approximation the LV_o from inlet to near the outlet and the velocity near the outlet was the lowest compared to other cases. As a result, the effectiveness of δ to η (β=0.69) in this case was the highest. However, in three cases, the *LV* was decreased by 2.73 times but a small reduction rate of velocity (lower than 2.73 times) was observed, so the coefficient β was always smaller compared to the ideal value of β=1.

From the study results, the best solution for improving SS removal efficiency in the settling tank was increasing the length. However, the settling tanks with increased length were difficult to be placed in the plant layout. In a further study, application the CFD model to estimate the effect of this type of configuration, as shown in **Fig. 11,** on the treatment efficiency of the tank should be performed. Instead of reducing the *LV* by increasing the width, flow direction should be arranged in a zigzag way to have similar treatment efficiency to increasing the length as above-mentioned. Thus, there is an optimal solution for the design to saving areas and easy organization layout of settling tanks.

At present, the improvement of η of the lamella settlers is continuously evolved. A possible approach is to optimize the arrangement of inclined plates, for example in parallel to the direction of the inlet flow [25,26]. This scenario should be simulated to reveal the optimal placement of inclined plates. To better visualize the effects, the simulation in 3-dimensional should be carried out.

CONCLUSION

The research evaluated the effect of δ on improving SS removal efficiency in the settling tank with three different types of configuration. Simulation results show that the η could be improved by increasing the δ. Specifically, the particle group with $\psi_{90\text{-}o}$, the ratio of $SV_{90\text{-}o}$ to LV_o equal 2.14, was removed with 90% in the original settling tank. With the same removal efficiency, in ideal condition, the ψ_{90} decreases from 2.14 to 1.07 (2 times reduction) as increasing δ to 1 for all three cases. However, in this study, the δ increased to 1 by installing inclined plates, increasing the length, and increasing the width, the ψ_{90} only decreased from 2.14 to 1.98, 1.73, and 1.26 respectively. Therefore, the δ could enhance the removal efficiency of small *SV* particle groups, but the effectiveness of δ in increased η was significantly lower than the ideal value of β = 1. It was noteworthy that the increased δ by increasing the length had the largest contribution to improve the η of small *SV* particle groups with β = 0.69. The result has important implications in the renovation design of settling tanks to get the best performance for the wastewater treatment plant.

REFERENCES

[1] Demir A: Determination of settling efficiency and optimum plate angle for plated settling tanks. *Water Res.*, **29**(2), 611–616, 1995. doi:10.1016/0043-1354(94)00165-4

[2] Kowalski WP: The method of calculations of the sedimentation efficiency in tanks with lamella packets. *Arch. Hydro-Eng. Environ. Mech.*, **51**(4), 371–385, 2004.

[3] Fujisaki K, Terashi M: Improvement of settling tank performance using inclined tube settlers. *WIT Trans. Ecol. Environ.*, **80**, 475-484, 2005.

[4] Leung WF: Lamella and tube settlers. 2. Flow stability. *Ind. Eng. Chem. Process Des. Dev.*, **22**(1), 68–73, 1983. doi:10.1021/i200020a012

[5] Degrémont: Water Treatment Handbook, Volume 1, 7th edition. Degrémont, Rueil-Malmaison, France, 2007.

[6] Metcalf and Eddy, Inc.: Wastewater Engineering: Treatment and Reuse, Fourth edition. Mc Gram-Hill, New York, USA, 2003.

[7] Stamou AI, Adams EW, Rodi W: Numerical modeling of flow and settling in primary rectangular clarifiers. *J. Hydraul. Res.*, **27**(5), 665–682, 1989. doi:10.1080/00221688909499117

[8] Goula AM, Kostoglou M, Karapantsios TD, Zouboulis AI: A CFD methodology for the design of sedimentation tanks in potable water treatment: Case study: The influence of a feed flow control baffle. *Chem. Eng. J.*, **140**(1-3), 110–121, 2008. doi:10.1016/j.cej.2007.09.022

[9] Asgharzadeh H, Firoozabadi B, Afshin H: Experimental investigation of effects of baffle configurations on the performance of a secondary sedimentation tank. *Sci. Iran.*, **18**(4), 938–949, 2011. doi:10.1016/j.scient.2011.07.005

[10] Shahrokhi M, Rostami F, Said Md Azlin Md, Syafalni: The Computational Modelling of Baffle Configuration in the Primary Sedimentation Tanks. 2nd International Conference on Environmental Science and Technology, Singapore City, Singapore, 2011.

[11] Heydari MM, Bajestan MS, Kashkuli HA, Sedghi H: The effect angle of baffle on the performance of settling basin. *World Appl. Sci. J.*, **21**(6), 829–837, 2013.

[12] Ghawi AH, Kriš J: A computational fluid dynamics model of flow and settling in sedimentation tanks. In: Oh HW (ed): Applied Computational Fluid Dynamics, IntechOpen, London, United Kingdom, pp. 19-34, 2012.

[13] Tarpagkou R, Pantokratoras A: The influence of lamellar settler in sedimentation tanks for potable water treatment — A computational fluid dynamic study. *Powder Technol.*, **268**, 139–149, 2014. doi:10.1016/j.powtec.2014.08.030

[14] Nguyen T, Dao NT, Liu B, Terashima M, Yasui H: Computational fluid dynamics study on attainable flow rate in a lamella settler by increasing inclined plates. *J. Water Environ. Technol.*, **17**(2), 76–88, 2019. doi:10.2965/jwet.18-044

[15] Mohanarangam K, Stephens DW: CFD Modelling of floating and settling phases in settling tanks. Seventh International Conference on CFD in the Minerals and Process Industries, Melbourne, Australia, 2009.

[16] Ghawi AH: Application of computational fluid dynamics modelling to a horizontal sedimentation tank in Iraq. *Int. J. Eng. Sci. Res. Technol.*, **6**(4), 1–8, 2017. doi:10.5281/zenodo.495142

[17] Japan Sewage Works Association: Design Standard for Municipal Wastewater Treatment Plants. Japan Sewage Works Association, Tokyo, Japan, 2013.

[18] Liu YL, Wei WL, Lv B, Yang XF: Research on optimal radius ratio of impellers in an oxidation ditch by using numerical simulation. *Desalination Water Treat.*, **52**(13-15), 2811–2816, 2014. doi:10.1080/19443994.2014.883045

[19] Wei W, Liu Y, Lv B: Numerical simulation of optimal submergence depth of impellers in an oxidation ditch. *Desalination Water Treat.*, **57**(18), 8228–8235, 2016. doi:10.1080/19443994.2015.1021840

[20] Stamou AI, Theodoridis G, Xanthopoulos K: Design of Secondary Settling Tanks Using a CFD Model. *J. Environ. Eng.*, **135**(7), 551–561, 2009. doi:10.1061/(ASCE)0733-9372(2009)135:7(551)

[21] Weiss M, Plosz BG, Essemiani K, Meinhold J: CFD modelling of sludge sedimentation in secondary clarifiers. *WIT Trans. Ecol. Environ.*, **52**, 509–518, 2006. doi:10.2495/AFM06050

[22] Wang X, Yang L, Sun Y, Song L, Zhang M, Cao Y: Three-dimensional simulation on the water flow field and suspended solids concentration in the rectangular sedimentation tank. *J. Environ. Eng.*, **134**(11), 902–911, 2008. doi:10.1061/(ASCE)0733-9372(2008)134:11(902)

[23] Liu Y, Zhang P, Wei W: Simulation of effect of a baffle on the flow patterns and hydraulic efficiency in a sedimentation tank. *Desalination Water Treat.*, **57**(54), 25950–25959, 2016. doi:10.1080/19443994.2016.1157521

[24] Patziger M, Kainz H, Hunze M, Józsa J: Influence of secondary settling tank performance on suspended solids mass balance in activated sludge systems. *Water Res.*, **46**(7), 2415–2424, 2012. PMID:22365174 doi:10.1016/j.watres.2012.02.007

[25] JFE Engineering Corporation: Pretreatment sedimentation equipment - Inclined plate settling device. http://www.jfe-eng.co.jp/products/environment/water_supply/sup02.html [accessed in August, 2019, in Japanese]

[26] SUEZ's degremont: SUEZ's degremont® water handbook, Lamella sedimentation. https://www.suezwaterhandbook.com/water-and-generalities/fundamental-physical-chemical-engineering-processes-applicable-to-water-treatment/sedimentation/lamellar-sedimentation [accessed in August, 2019]