Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25157

183 (2020) 23–29
April

Simulating the behavior of ballasted flocs in circular lamellar settling tank using computational fluid dynamics (CFD)

Ki-Yeon Kim[§], Seongjun Park[§], Won-Hee Lee, Jong-Oh Kim*

Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Korea, Tel. +82-2-2220-0325; Fax. +82-2- 2220 1945; email: jk120@hanyang.ac.kr (J.-O. Kim)

Received 1 July 2019; Accepted 18 November 2019

ABSTRACT

The separation process of water treatment such as coagulation/flocculation separates various particle matters from water using specific gravity differences. Among several particle separation technologies, the ballasted flocculation (BF) process has recently been proposed to cope with water quality changes due to climate change. Each technology of the BF process is designed to maximize the particle removal efficiency of the whole process. The removal efficiency of the separation process is affected by not only floc characteristics but also hydraulic characteristics, resulting in the short-circuiting flow, dead-zone due to the density difference formed by temperature and specific gravity of the liquid, and the turbulence caused by the shape of the inlet and outlet. The circular lamellar settling tank can reduce a short-circuiting flow and dead-zone. In addition, it can reduce the settling distance and the settling time of suspended solid, while the increased effective sedimentation area can increase the sedimentation efficiency per unit volume. However, if the lamellar plate is designed improperly, the flocs to be removed inevitably release to effluent or accumulate on the plate, which affects the water quality negatively. Therefore, in this study, to confirm the removal efficiency of ballasted flocs according to the angle of the lamellar plate in a circular lamellar settling tank, we simulate the effect of changing the plate angle using computational fluid dynamics (CFD). CFD simulation was conducted to estimate the particle inflow ratio into the lamellar module, the particle removal efficiency of the lamellar module, and the whole particle removal efficiency of the circular lamellar settling tank. The particle inflow ratio into the lamellar module is the smallest at 60° of lamellar plate, while the specific gravity and the size of particles are smaller. This phenomenon shows that the sedimentation force by gravity is predominant. The particle removal efficiency of the lamellar module was also the highest at 60° of lamellar plate.

Keywords: Ballasted flocculation; Lamellar settling tank; Angle of lamellar plate; Behavior of particles

1. Introduction

Droughts and floods frequently occur due to rapid climate change. These phenomena cause changes in the water quality of the raw water flowing into the water treatment system. Rapidly changing the quality of the influent affects the efficiency of the system, which negatively affects the quality of the effluent at a conventional water treatment system [1,2]. Therefore, there is a need for a technology that can respond quickly and efficiently to an increased flow rate and a high concentration of pollutants. As one of the solutions to this problem, a ballasted flocculation (BF) process that can increase the surface loading rate by 40–100 times compared to the conventional system has been widely proposed [3–5]. A typical BF process consists of mixing zone, settling zone and ballast recovery zone. In addition, each process is designed to increase the surface loading rate by increasing settling efficiency. Actiflo Turbo® (Veolia Water Co. Ltd., France)

* Corresponding author.

§Joint first authorship.

and Densadeg® (Degremont Inc., France) are representative BF process. Both processes use microsand and return sludge, respectively, as ballast which acted as the floc's seed to increase settling velocity. Also, by installing the inclined plates inside the settling tank, the settling area was increased and settling efficiency was improved [6–8]. These settling technology are to maximize process capacity and efficiency at limited foot-print. In particular, the application of the inclined plate has the advantage that the flow can be kept as laminar flow as possible while the settling distance is shortened. It can reduce the settling distance and the settling time of suspended solid, while the increased effective sedimentation area can increase the sedimentation efficiency per unit volume [9]. Therefore, this maximizes hydrodynamic stability and settling efficiency. When designing a lamellar module, the number of plates, the distance between the plates, angle and size must be considered to achieve high settling efficiency. If the lamellar plate is designed improperly, the flocs to be removed inevitably release to effluent or accumulate on the plate, which affects the water quality negatively, so establishing the optimum design parameter is essential [10]. When the lamellar module is installed to improve the settling efficiency, the settling distance (h) is shortened from plate length (H), and the settling efficiency is known to increase by plate angle (θ) times. The cosine θ tends to decrease as the angle of inclined plate increases, and the settling efficiency estimation of the lamellar settling tank is carried out under ideal conditions. The angle of the inclined plate is usually designed according to guidelines when designing a lamellar module. However, the removal efficiency of solid-liquid separation processes is known to be affected by many factors [11]. Demir [12] reported the optimal angle range of lamellar plate with 40° to 60°, and Doroodchi et al. [13] evaluated particle removal efficiency on 70° lamellar plates. Nir and Acrivos [14] reported that sediment can maintain a constant flow only above the minimum angle of inclination. Laskovski et al. [15] considered the Reynolds number according to the aspect ratio and the angle of the lamellar plate and reported the correlation between floc density and size. Among several lamellar design factors, the change in angle is a significant factor for the floc removal efficiency, and several researchers have focused on the change in angle for various types of solid-liquid separation in various settling tanks. The removal efficiency of the separation process is affected by not only floc characteristics but also hydraulic characteristics, resulting in the short-circuiting flow, dead-zone due to the density difference formed by temperature and specific gravity of the liquid, and the turbulence caused by the shape of the inlet and outlet [16]. The circular lamellar settling tank can reduce a short-circuiting flow and dead-zone [17]. The BF process aims at a higher surface loading rate and higher settling velocity of the ballasted flocs than the conventional process. Although it is ideal to examine the various design factors of the lamellar plate according to the characteristics of the floc to apply the circular lamellar settling tank in the BF process, there are experimental limitations (cost, time, etc.). Therefore, computational fluid dynamics (CFD) analysis can be the best alternative. CFD is a computer-based analysis technique to express physical and chemical phenomena (fluid flow, heat transfer, and chemical reaction, etc.) as governing equations. Not only CFD analysis can provide information on complex fluid dynamics as the design and initial conditions change, but also it is possible to save time and cost due to free from various scenarios that can be set freely [18,19].

In this study, we use the CFD software to apply the circular lamellar settling tank in the BF process. To understand the actual phenomena in the circular lamellar settling tank, we evaluate the various property of ballasted floc. The purpose application of the lamellar module is to take the stable fluid flow and the high settling efficiency. Therefore, we evaluated the floc removal ratio and behavior at the circular lamellar settling tank and lamellar module according to the change of the inclined plate angle.

2. Materials and methods

2.1. Modeling the circular lamellar settling tank for CFD analysis

The circular lamellar settling tank for CFD modeling was designed with a capacity of 300 m^3/d and a surface loading rate of 40 m^2/m h. The lamellar plate was applied to maximize the settling area and to increase the settling efficiency of flocs as shown in Fig. 1. Lamellar plate design factors include the size, gap, number of plates, and angle. The plate angle is one of the factors affecting the settling distance, which greatly affects the removal efficiency of the flocs [12]. Therefore, the circular lamellar settling tank was designed to 4 cases ranging from 50° to 65° at every 5° intervals. And a count of 7 inclined plates of the same configuration was installed at 50 mm distance interval in tanks, respectively. The detailed geometric design parameters of the circular lamellar settling tank are summarized in Table 1.

2.2. Estimate of inlet condition

To realize the actual process as possible, the inlet particle was based on the previous study. In the previous study, they used the image analysis device to analyze the property of the ballasted flocs. To guarantee more than 95% confidence, ballasted flocs of 40 were measured. The ballasted flocs showed a diameter of 700 to 1,500 μm and a specific gravity of 1.02 to 1.09 depending on the ballast dosage as shown in Fig. 2 [20]. Therefore, 9 kinds of particles were considered. Meanwhile,

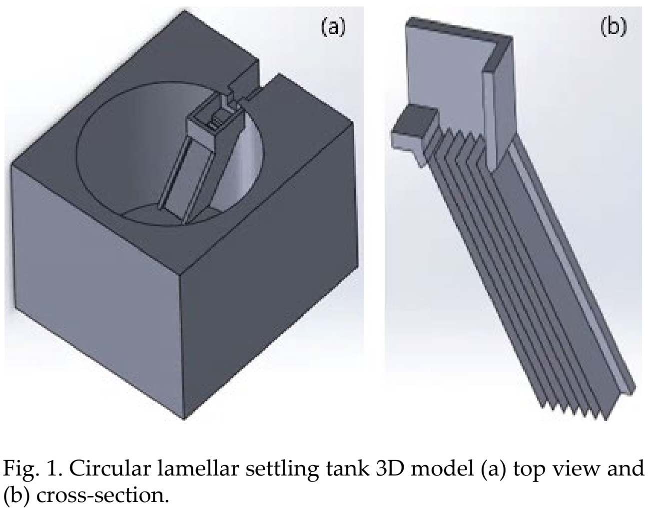

Fig. 1. Circular lamellar settling tank 3D model (a) top view and (b) cross-section.

Table 1
Characteristics of circular lamellar settling tank

Division	Value
Inlet flow rate	300 m^3/d
Surface loading rate	40 m^2/m h
Volume of settling tank	6.28 m^3
Height of settling tank	2 m
Diameter of settling tank	2 m
Hydraulic residence time	30 min
Size of lamellar plate	0.3 m (W) × 0.9 m (L)
Angle of lamellar plate	50°, 55°, 60°, 65°
Distance of lamellar plate	50 mm

the capacity of 300 m^3/d raw water contains up to 1,200–1,300 mg/L of the ballasted floc. Increasing the raw water concentration in the water treatment process have a negative effect on the effluent quality [1,2]. The CFD modeling was conducted under the conditions of the maximum inlet concentration (number of particles) to prove the performance of the circular lamellar settling tank. And each particle ratio was set equal to evaluate the removal efficiency and behavior of each ballasted floc, independently. The detailed information of the inlet particle is summarized in Table 2.

2.3. CFD analysis

Flow-3D (ver. 11.2, Flow Science, Inc., USA) was used as a CFD software to model the circular lamellar settling tank. The mesh can be generated with the Flow-3D program, and the normal mesh size is set to 50 mm. At least two meshes must be included to model narrow geometry in Flow-3D. Since the fluid flow is narrowed by the lamellar module, the mesh size is applied by using the multi mesh blocks as shown in Fig. 3. The number of meshes applied to model the distance of the lamellar plate is 4 or more. The analysis time increase when the number of meshes for CFD analysis was increased. If the geometry to be used for CFD analysis has perfect symmetry, only half of the geometry can be analyzed to save time. The number of mesh for the analysis of half geometry is about 88,000. The turbulence model used in the analysis was a renormalized group (RNG) model. The standard k–ε model is known to be somewhat inaccurate in the low range of Reynolds number and vortex flow, but it has been used in many cases in CFD analysis due to the advantage of good convergence and short calculation time when calculating complex flows. The RNG model has a constant empirically found and has broader applicability than other similar turbulence models such as the k–ε model [21–24]. The particle with a specific gravity of 1.03, 1.06 and 1.09 was prepared as particle diameter of 500, 1,000 and 1,500 μm to analyze the settling efficiency of floc in a circular lamellar settling tank. The detailed information on the CFD analysis is summarized in Table 3.

2.4. Definition and calculation related to particle efficiency

The total removal efficiency of a circular settling tank was calculated to evaluate the performance by the change of the plate angle. To understand the behavior of the particles, we calculated the removal efficiency of the lamellar module and the inflow ratio into the lamellar module. The baffles for counting the accumulated number of particles was installed to calculate each ratio. The estimation of an accumulated

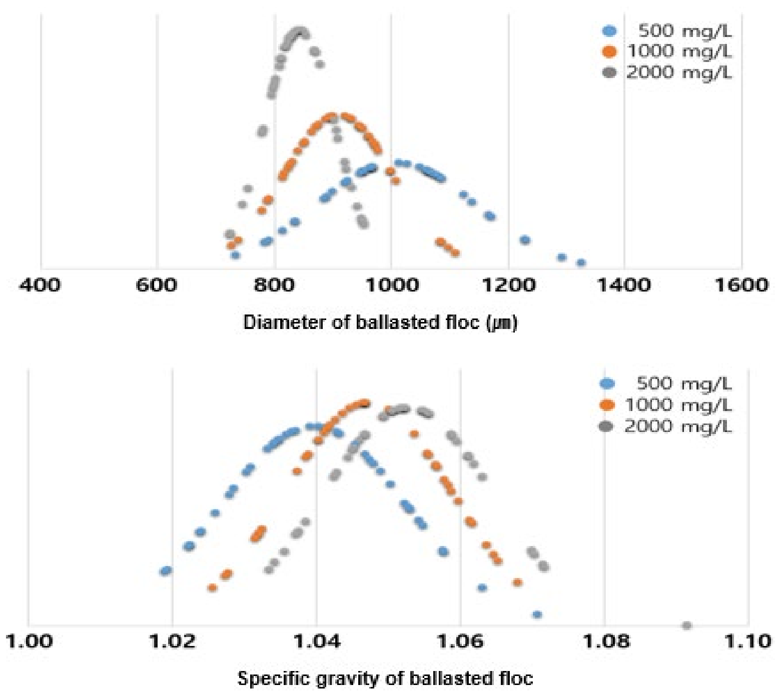

Fig. 2. Ballasted floc characteristics by ballast dosage in the previous study.

Table 2
Calculation of inlet particles at a capacity of 300 m^3/d

Division	Particle								
	A	B	C	D	E	F	G	H	I
Diameter (μm)	500	1,000	1,500	500	1,000	1,500	500	1,000	1,500
Specific gravity	1.03	1.03	1.03	1.06	1.06	1.06	1.09	1.09	1.09
Weight of particle (mg/particle)	0.0674	0.5390	1.8192	0.0693	0.5547	1.8722	0.0713	0.5704	1.9252
Fraction	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Number of inlet particle	Each 600/(Total 30,000,000)								

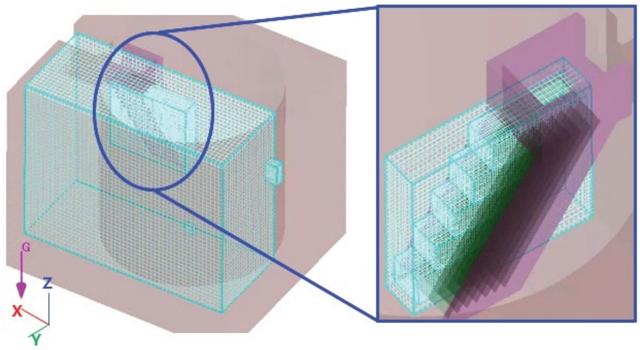

Fig. 3. Multi mesh block of circular lamellar settling tank.

Table 3
Simulation condition of circular lamellar settling tank

Division	Value
Inlet flow rate	300 m^3/d
Angle of lamellar plate	50°, 55°, 60°, 65°
Mesh size	Normal size: 50 mm
	Minimum size: 12.5 mm
Number of mesh	About 88,000
Solution time	45 min (1.5 HRT)
Data interval time	5 s
Turbulence model	Renormalized group (RNG) model
Boundary conditions	X Max (atmospheric pressure)
	Z Max (atmospheric pressure)

particle in each baffle was considered for a steady-state after 1 HRT (hydraulic retention time). Therefore, each efficiency was calculated based on 1 to 1.5 HRT. The removal ratio and the inflow ratio into the lamellar module can be calculated as follows:

$$E_{\mathrm{TR}} = \frac{(m_T - m_o)}{m_T} \quad (1)$$

$$E_{\mathrm{LR}} = \frac{(m_i - m_o)}{m_i} \quad (2)$$

$$E_{\mathrm{LI}} = \frac{m_i}{m_T} \quad (3)$$

3. Results and discussion

3.1. Particle size and specific gravity affecting inflow ratio and removal efficiency at lamellar module

Fig. 4 shows the particle inflow ratio and the particle removal efficiency of the lamellar module varying with particle size and specific gravity according to the angle change of circular lamellar settling tank. Overall, the inflow ratio of the lamellar module decreased as the particle size and specific gravity increased. This phenomenon indicates that gravity prevails within the settling tank before inflowing the lamellar module. The particle inflow ratio of the lamellar module was the lowest at 60° of the lamellar plate, and the particle removal efficiency of the lamellar module was the highest at 60° of lamellar plate.

3.2. Particle behavior in lamellar module by Reynolds number

As shown in Fig. 4, the removal efficiency of each particle shows a pattern having an inflection point rather than a constant increase or decrease. The separation efficiency of a particle in a fluid depends on the forces acting on a particle. In particular, when three or more forces act on a particle, it shows specific particle separation characteristics. A typical example is hydrocyclone. Three kinds of forces act on the particles such as centrifugal force, gravity and buoyant force at the hydrocyclone inside. Finally, it shows a particle separation characteristic called fish-hook. Inside the lamellar module, the forces act on the particles such as force by fluid flow, gravity and buoyant force as shown in Fig. 5. The variation in particle removal efficiency at the lamellar module exhibits specific particle separation characteristics because three or more forces act on the particles. Stokes' law is the ideal expression of the settling velocity of particles having a sphere shape under ideal conditions. A general form of Stokes' law is known to be sufficient in water treatment [25]. This formula transforms depending on the properties of the applied particles. When expressing the settling velocity of the general floc, the relation between drag coefficient and Reynolds number is modified according to the shape factor [26]. If Reynolds number is large, Allen or Newton formula may be used depending on the specific gravity and size of the particle.

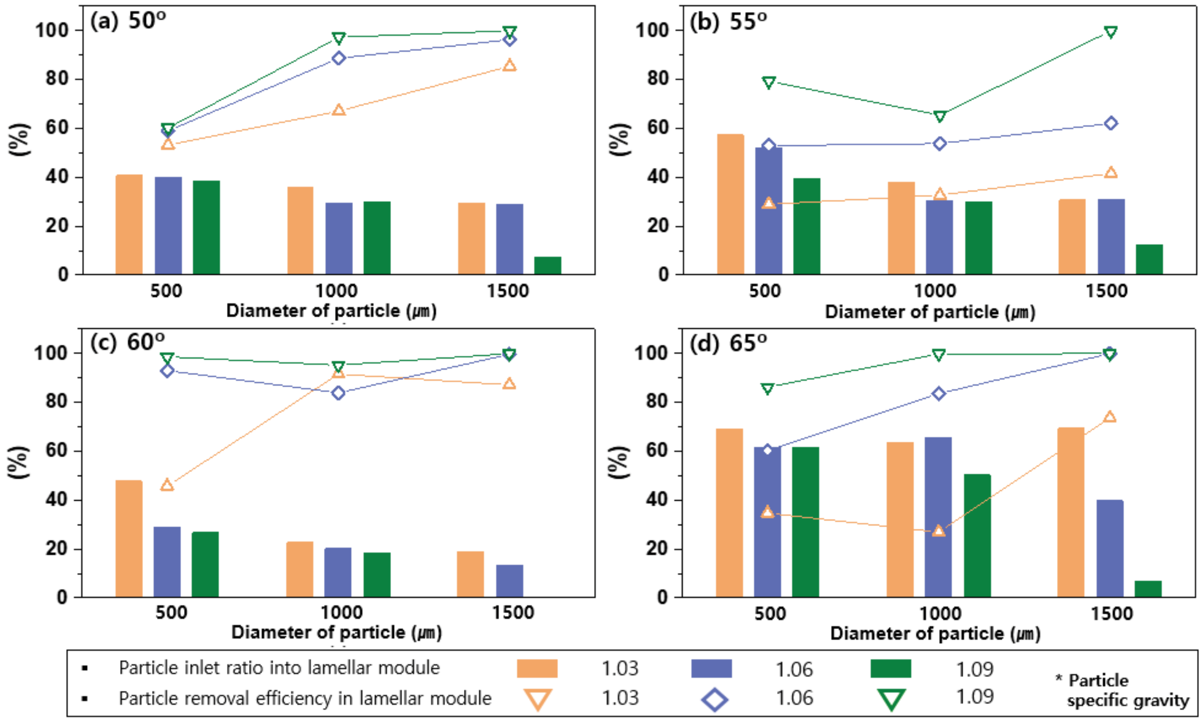

Fig. 4. Particle inflow ratio and removal efficiency of lamellar module at (a) 50°, (b) 55°, (c) 60°, and (d) 65°.

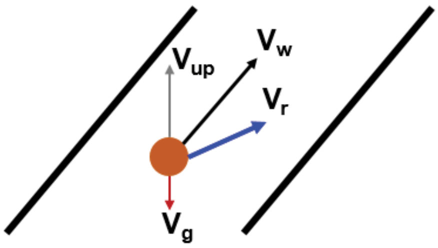

Fig. 5. Resultant particle velocity in lamellar module [27].

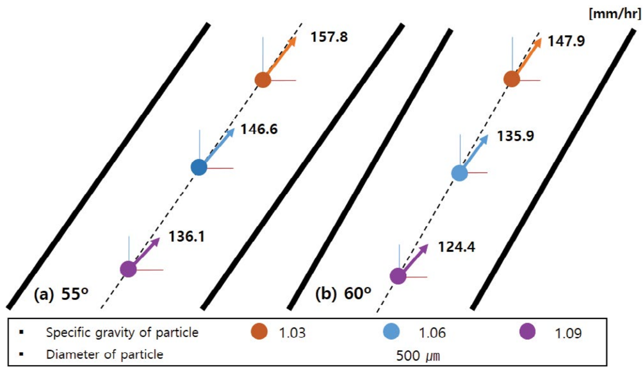

Fig. 6. Particle behavior in (a) 55° and (b) 60° lamellar module.

To evaluate the difference in the behavior of particle at the lamellar module, it is shown in Fig. 6 based on the 500 μm particles which are the most sensitive in particle removal efficiency. It is based on the 55° lamellar module with the worst particle removal efficiency and the 60° lamellar module with the best particle removal efficiency. The resultant particle velocity (V_r) in Fig. 6 is the sum of the settling velocity which determined by the buoyant force and gravity and the up-flow velocity due to the fluid flow. As a result, the particle velocity vector on the 60° lamellar module is lower, and the angle with the inclined plate tends to be greater, which has a more favorable effect on particle removal efficiency.

3.3. Particle removal efficiency by the angle of inclined plate

Table 4 shows the particle removal efficiency varying with plate angle in the circular lamellar settling tank. It shows the lowest removal efficiency at a 55° circular lamellar settling tank. While, at 60° circular lamellar settling tank, the removal efficiency was 96.7% to 99.9% or more except for particle A. As shown in Fig. 7, it shows the removal efficiency of 55° with the worst and 60° with the best as a trend graph in the circular lamellar settling tank. The removal efficiency trend of 55° circular lamellar settling tank shows an inflection point in certain areas, which can be a barrier to ensuring stable treatment water quality. On the other hand, the removal efficiency trend of the 60° circular lamellar settling tank is more stable with shifted to the left. And the removal efficiency is more linear contour. Therefore, when the 60° of lamellar module is applied to the circular settling tank, it is considered that the treatment efficiency can be relatively easily achieved.

4. Conclusion

We were adopted a circular lamellar settling tank to minimize short-circuiting flow and dead-zone. The CFD analysis

Table 4
Particle removal efficiency of circular lamellar settling tank

Particle division	Diameter (μm)	Specific gravity	Value (%)			
			50°	55°	60°	65°
A	500		80.89	59.35	74.03	54.82
B	1,000	1.03	88.13	74.36	98.10	53.72
C	1,500		95.72	82.10	97.59	81.75
D	500		83.60	75.59	98.00	75.69
E	1,000	1.06	96.67	85.88	96.74	89.21
F	1,500		98.94	88.23	99.96	99.99
G	500		84.66	91.80	99.65	91.51
H	1,000	1.09	99.21	89.64	99.12	99.99
I	1,500		99.99	99.99	99.99	99.99

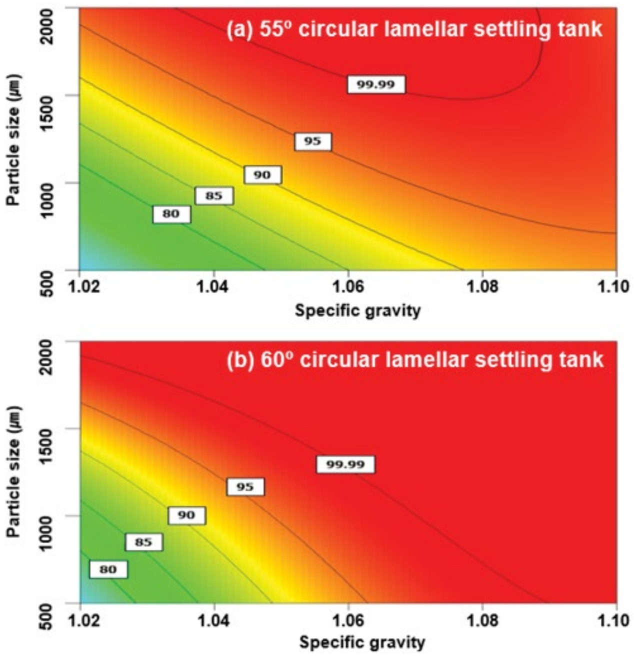

Fig. 7. Trend of particle removal efficiency of (a) 55° and (b) 60° circular lamellar settling tank with the change of particle size and specific gravity.

was conducted to estimate the optimal conditions for the angle of the lamellar plate according to the characteristic of the settling tank. We were evaluated various sizes of ballasted floc with a specific gravity of 1.03 to 1.09 and size of 500 to 1,500 μm to improve treatment efficiency and to apply the circular lamellar settling tank in the BF process. The removal efficiency shows 96.7%–99.9% or more except for particle A at 60° circular lamellar settling tank. The particle removal efficiency shows a specific separation characteristic such as fish-hook according to the change of the inclined plate angle and particle property. Since the removal efficiency variation of particle and up-flow velocity of particle were the smallest at the 60° lamellar module, stable treatment efficiency can be expected. As a result, the total particle removal efficiency in a 60° circular lamellar settling tank shows linear in the plotted trend graph. Based on this graph, we can determine the floc properties needed to achieve target treatment efficiency in the BF process.

Acknowledgment

This subject is supported by the Korea Ministry of Environment as "Global Top Project (2016002110006)".

Symbols

E_{TR} — Removal efficiency of the circular settling tank
E_{LR} — Removal efficiency of the lamellar module
E_{LI} — Inflow ratio into the lamellar module
m_T — Number of total inlet particles
m_i — Accumulated number of particles entering the lamellar module
m_o — Accumulated number of particles in the effluent
V_W — Water flow velocity
V_{up} — Up-flow velocity
V_g — Acceleration due to gravity
V_r — Resultant particle velocity
θ — Inclined plate angle of the lamellar module
A — Surface area of settling tank
a — Area of inclined plate

References

[1] S. Park, Y. Moon, J.O. Kim, Evaluation of the image analysis method using statistics for determining the floc size and settling velocity in ballasted flocculation, Desal. Wat. Treat., 99 (2017) 220–227.
[2] I. Delpla, A.V. Jung, E. Baures, M.C. Lement, O. Thomas, Impacts of climate change on surface water quality in relation to drinking water production, Environ. Int., 35 (2009) 1225–1233.
[3] C. Desjardins, B. Koudjonou, R. Desjardins, Laboratory study of ballasted flocculation, Water Res., 36 (2002) 744–754.
[4] S.S. Borchate, G.S. Kullkami, V.S. Kore, S.V. Kore, A review on applications of coagulation-flocculation and ballast flocculation for water and wastewater, Int. J. Innovative Eng. Technol., 4 (2014) 216–222.
[5] C. Levecq, C. Breda, V. Ursel, P. Marteil, P. Sauvignet, A new design of flocculation tank: the Turbomix® applied to weighted flocculation, Water Sci. Technol., 56 (2007) 141–149.
[6] X.D. Pan, H.B. Xu, W.Y Wei, Application and development status of ballasted flocculation technology, China Water Wastewater, 23 (2007) 1–4.
[7] E. Imasuen, S. Judd, P. Sauvignet, High-rate clarification of municipal wastewaters: a brief appraisal, J. Chem. Technol. Biotechnol.: Int. Res. Process Environ. Clean Technol., 79 (2004) 914–917.
[8] United States Environmental Protection Agency, Wastewater Technology Fact Sheet: Ballasted Flocculation, U.S. EPA Office of Water, Washington, D.C., USA, 2003.
[9] N.T. Dao, B. Liu, M. Terashima, H. Yasui, Computational fluid dynamics study on attainable flow rate in a lamella settler by increasing inclined plates, J. Water Environ. Technol., 17 (2019) 76–88.
[10] S. Kim, A Study on Optimal Design for Inclined-tube Settling Tank by Computational Flow Analysis, Suwon University, Korea, 2013.
[11] Y. Kim, Comparison of the Hydraulic Behavior and Sedimentation Efficiencies of Horizontal-flow Sedimentation basin and Upflow Sedimentation Basin, Kongju University, Korea, 2010.
[12] A. Demir, Determination of settling efficiency and optimum plate angle for plated settling tanks, Water Res., 29 (1995) 611–616.

[13] E. Doroodchi, J. Zhou, D.F. Fletcher, K.P. Galvin, Particle size classification in a fluidized bed containing parallel inclined plates, Miner. Eng., 19 (2006) 162–171.
[14] A. Nir, A. Acrivos, Sedimentation and sediment flow on inclined surfaces, J. Fluid Mech., 212 (1990) 139–153.
[15] D. Laskovski, P. Duncan, P. Stevenson, J. Zhou, K.P. Galvin, Segregation of hydraulically suspended particles in inclined channels, Chem. Eng. Sci., 61 (2006) 7269–7278.
[16] S. Jayanti, S. Narayanan, Computational study of particle-eddy interaction in sedimentation tanks, J. Environ. Eng., 130 (2004) 37–49.
[17] J. Huang, Y.C. Jin, Numerical modeling of Type I circular sedimentation tank, J. Environ. Eng., 137 (2010) 196–204.
[18] B. Wang, K. Chu, A. Yu, Numerical study of particle − fluid flow in a hydrocyclone, Ind. Eng. Chem. Res., 46 (2007) 4695–4705.
[19] A.M. Goula, M. Kostoglou, T.D. Karapantsios, and A.I. Zouboulis, 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 (2007) 4695–4705.
[20] Y. Moon, Characteristics of Ballasted Flocs in Static Mixer Using Image Analysis Method, Hanyang University, Korea, 2018.
[21] C.G. Speziale, S. Thangam, Analysis of an RNG based turbulence model for separated flows, Int. J. Eng. Sci., 30 (1992) 1379–1388.
[22] W.D. Griffiths, F. Boysan, Computational fluid dynamics (CFD) and empirical modelling of the performance of a number of cyclone samplers, J. Aerosol Sci., 27 (1996) 281–304.
[23] Y. Jeon, Fluid Flow Analysis of Inclined Plate Settler by using CFD, Inha University, Korea, 2009.
[24] K.Y. Kim, S. Park, W.H. Lee, J.O. Kim, Computational fluid dynamics (CFD) modeling of hydrocyclone for the recovery of ballasts and removal of sludge floc in ballasted flocculation process, Desal. Wat. Treat., 143 (2019) 29–37.
[25] S. Choi, Settling Efficiency of Problematic Algae and Their Flocculants in the Water Treatment Process, Inje University, Korea, 2004.
[26] H. Yang, M. Fan, A. Liu, L. Dong, General formulas for drag coefficient and settling velocity of sphere based on theoretical law, Int. J. Min. Sci. Technol., 25 (2015) 219–223.
[27] C.P. Vesga-Rodríguez, L.D. Donado-Garzón, M. Weber-Shirk, Evaluation of high rate sedimentation lab-scale tank performance in drinking water treatment, Revista Facultad de Ingeniería, 90 (2019) 9–15.