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Advanced total phosphorus removal approach: system design and combined sewer overflows (CSOs) sludge application

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ABSTRACT

Advanced total phosphorus (TP) removal is required to regulate the TP concentrations to less than 0.2 mg/L, as specified by the South Korean policies for the prevention of aquatic eutrophication. In order to meet the standards from 2012, the treatment efficiency of conventional treatment plants should be improved. This study addresses this need by developing a novel TP removal methodology that uses a static mixer for coagulation and a redesigned sedimentation tank incorporated with a guiding baffle. Experiments were carried out during summer, autumn, and winter. Results show that: (1) the phosphorus removal efficiency was relatively higher in summer than in autumn and winter, (2) the inline static mixer increased the efficiency of soluble phosphorus removal to above 95%, and (3) optimal angle determination for the guiding baffle was essential to achieve a stable hydraulic behavior and a low shear rate at the bottom of the sedimentation tank and thus to improve the sedimentation rate. In addition, the application of combined sewer overflows sludge led to stable and high phosphorus removal efficiency (> 90%). These results indicate that the newly designed TP removal plant could serve as a prototype for an advanced treatment of phosphorus in wastewaters.

Keywords: Phosphorus removal; Inline static mixer; Guiding baffle; CSOs' sludge

1. Introduction

Nutrients, including phosphorus, are extensively used for agricultural production and industrial development for the last several decades. However, previous studies revealed that the presence of high concentrations of phosphorus in an aquatic system causes eutrophication in the rivers or lakes [1,2]. Without any treatment, eutrophication would threaten the lives of fish and livestock that depend on waterbodies [2]. Thus, controlling the phosphorus concentration level

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has become an important issue for water environmental protection in many countries, including South Korea [3]. In an effort to reduce water pollution, in 2012, the Korean government made a regulation to reduce the phosphorus concentration of effluents from wastewater treatment plants (WWTPs) from 2 to 0.2 mg/L [4].

Since the current conventional phosphorus treatment plants could not meet the new regulation, various innovative strategies to improve the efficiency of phosphorus removal were extensively explored. Chemical precipitation technology for phosphorus removal was first introduced in 1950s to treat the aquatic eutrophication problem in Switzerland [2]. Since then, chemical technology has been the leading strategy for the removal of phosphorus from waste water in many countries, such as Korea and United Kingdom due to its flexibility and relatively high efficiency [2,5,6]. Moreover, crystallization technology has been introduced as another option to increase nitrogen removal through a combination of crystallization and chemical precipitation. Therefore, improvements for the chemical precipitation technology have been sought for higher phosphorus removal efficiency and lower operating cost.

Our recent research focused on the physicochemical precipitation method due to its high phosphorus removal efficiency. Several previous studies [7–12] have shown that Ultra-Rapid Coagulation (URC) treatment had a high efficiency for phosphorus removal because of its improved coagulation/flocculation process, which can directly affect the precipitation performance. This technology has been widely applied in Korea and many optimal operational conditions have been established from advanced studies [5,12].

Based on the URC, a new approach for designing total phosphorus (TP) removal in water treatment plants was studied. By using an inline mixer (for the coagulation process) and a newly designed sedimentation tank, higher phosphorus performance than the current system was expected. Also, a new integral method was designed by applying the sludge from combined sewer overflows (CSOs) to the phosphorus removal process. The work reported here could regulate the phosphorus concentration in the final effluent to less than 0.2 mg/L.

2. Materials and methods

2.1 Site description

The secondary effluent from Gwangju City Environmental Installations Corporation, as illustrated in Fig. 1, was used as incoming wastewater for the newly designed phosphorus removal plant (NDPRP).

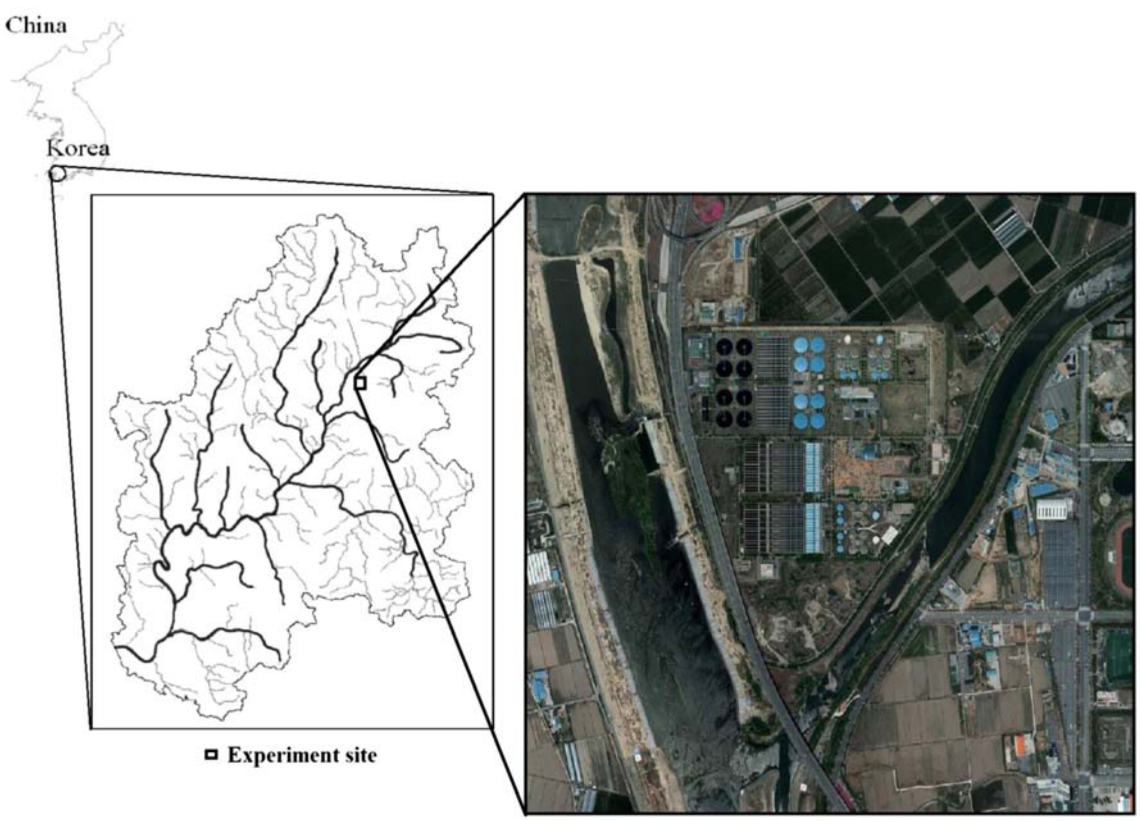

Fig. 1. Location of experimental site, showing the Gwangju City Environmental Installations Corporation in Korea.

The NDPRP consists of three treatment parts: coagulation part, flocculation tank, and sedimentation tank. The reagents used in the present study were alum or liquid phase of aluminum hydroxide $Al(OH)_3$ as a coagulant and anionic polymer of polyacrylamide for the flocculation process. In this case, no coagulation aid was used. COD_{Mn}, TSS, TN, TP, soluble total phosphorus (STP), alkalinity, and turbidity of water samples were evaluated by Standard Methods and are used as parameters of water quality.

2.2. Experimental procedures

Studies about the mol ratio of Al to P were undertaken through laboratory test and *in situ* experiment. Jar test was completed to determine the optimal dosage of alum for the coagulation process. During the laboratory test, alum was added under the stirring condition and experimental value of the revolutions per minute was 320 (G value = 300 s^{-1}). The reaction time was 1 min ($G \times t$ = 1,800). The same experimental conditions were applied to the *in situ* NDPRP to optimize the optimal mol ratio of Al to P. The amount of anionic polymer was fixed to the 0.7 mg/L for phosphorus removing process, whereas 1 mg/L for CSOs treatment.

In this study, sludge was recycled both during the dry days (for the TP removal process) and during the wet days (for the CSOs treatment). Additionally, we recycled the CSOs sludge during the dry day (to the TP removal process). Comparison of these two experiments would be used to evaluate the effect of CSOs sludge application to phosphorus removal treatment.

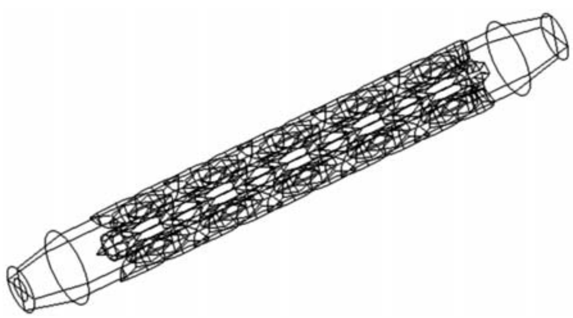

Fig. 2. Geometric view of the inline static mixer.

2.3. System designs

2.3.1. Inline mixer

Conventional URC technology contains two parts for the coagulation process: coagulation tank and coagulation-aid tank [12]. Of the various types of inline static mixers used in many different environmental studies, we adopted the diamond inline static mixer for the present research as illustrated in Fig. 2.

2.3.2. Sedimentation tank

Hydrological behavior in the sedimentation tank is an important factor for improving the phosphorus removal. One thousand (1,000) tons/day-scale waste treatment sedimentation tank was designed. The incoming water to the sedimentation tank was secondary wastewater, which was treated after the coagulation and flocculation stages.

The key elements of the sedimentation tank design were focused on the hydraulic behavior that may determine the behavior of suspension solids and the

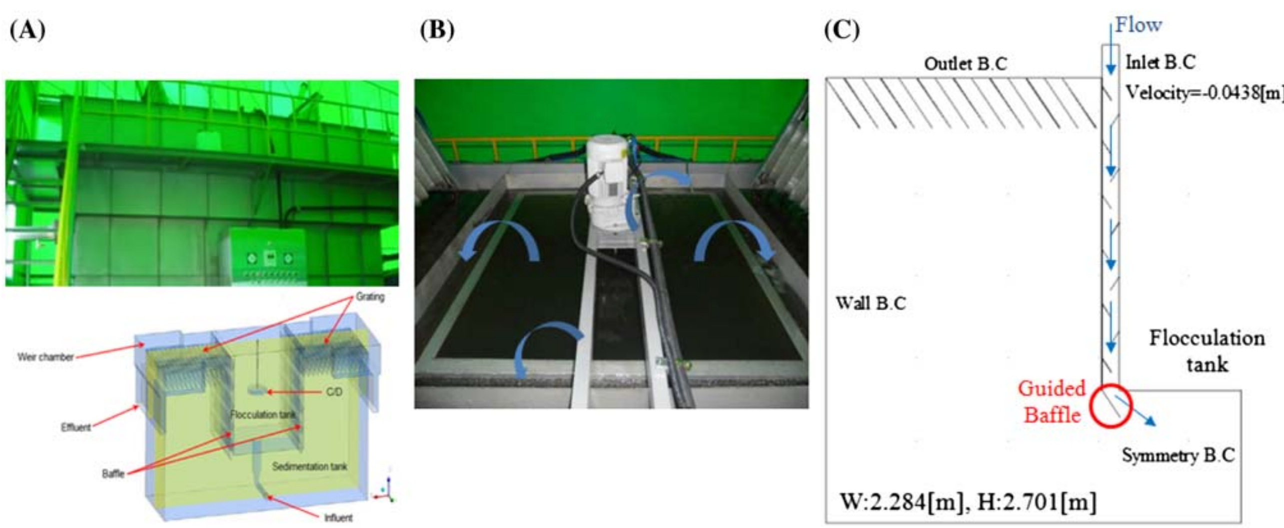

Fig. 3. Schematic of sedimentation: (A) front view (B) top view, and (C) cross section (W: width, H: height).

flow pattern inside the sedimentation tank. Fig. 3 presents the 3D-schematic diagram of the sedimentation tank. Flocculation tank was designed to be inserted into the sedimentation tank. Separating the water coming into the sedimentation tank into four directions could lead to a stable and slow inflow rate to the sedimentation tank, as shown in Fig. 3(B). Inclusion of the guiding baffle is another critical design parameter. The guiding baffle could reduce the shear rate and determine the size of the recirculation zone inside the sedimentation tank. The smaller the recirculation zone, the greater the settling of solids by sedimentation, and thus, less energy cost [12].

Computational fluid dynamics (CFD) study was conducted to evaluate the hydrodynamic performance of the sedimentation tank using 2D symmetric model. k-ϵ model for the turbulent flow was selected, and the sedimentation tank was simulated using inflow, outflow, wall, and symmetric boundary conditions as illustrated in Fig. 3(C). Steady state was assumed by using water as the inflow fluid. Numerical simulations were performed using COMSOL Multiphysics 3.5.

2.4. Statistical analyses

The data were analyzed using multi-way ANOVA with SPSS 17.0.1 for Windows release to determine the influence of seasons (pH, temperature, etc.), system design, and CSO sludge recycling methodology. Post hoc Scheffe test was carried out to determine the interaction between the seasonal effects on the process.

3. Results and discussions

3.1. Seasonal analysis

Tables 1 and 2 shows the seasonal variations in pH, TP, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and suspended solid (SS) of the influent and effluent for the NDPRP. The values of pH and coagulant dosage were considered as key parameters for the evaluation of NDPRP performance. The optimal pH in the previous chemical precipitation technologies varied from 5.5–7.5 [1,12–14]. The pH of the influent water in this study was in the range of 6.4–6.8, which is in accordance with previous observations, and showed no seasonal variations. The TP concentration in the influent water was significantly higher in summer (1.09 ± 0.40 mg/L) than in autumn (0.72 ± 0.34 mg/L) and winter (0.88 ± 0.37 mg/L) (one-way ANOVA, $p < 0.05$), with no significant difference between the latter two seasons. BOD was the highest in winter, whereas the COD was the lowest in summer, the values in the other two seasons being not significantly different between each other in both cases (one-way ANOVA, $p > 0.05$). In this study, no apparent seasonal variation in pH with large difference in removal efficiencies may suggest that the pH was not a key parameter for the performance of the NDPRP.

In an attempt to explore other parameters, we set the same dose of Al to P mol ratio for coagulants for all three seasons. From the jar test and *in situ* experiment, we previously found that the optimal dose mol ratio was about $2.5 \sim 3$:1. Under these conditions, the efficiency of phosphorus removal from secondary wastewater varied markedly with season: 87% in summer, 83% in autumn, and 74% in winter.

By increasing the temperature differential potential, the efficiency of phosphorus removal as well as sedimentation declined, especially in winter, as observed in a previous study [4]. Coefficient of variation (CV) for summer (CV = 0.06) is lower than that for winter (CV = 41.06) and autumn (CV = 0.09), indicating relatively small temperature variations in summer as compared with other seasons.

Table 1
Characteristics of influent to the NDPRP

	Ari. mean	Max	Min	Ari. mean	Max	Min	Ari. mean	Max	Min
	pH_{in}			$P_{tot\ in}$ (mg/L)			SS_{in} (mg/L)		
Summer	6.59 ± 0.25	7.34	6.32	1.09 ± 0.40	1.80	0.23	13.50 ± 7.11	33	4
Autumn	6.47 ± 0.13	6.74	6.37	0.72 ± 0.34	1.58	0.17	12.27 ± 6.68	30.5	6
Winter	6.52 ± 0.07	6.67	6.43	0.88 ± 0.37	1.97	0.30	13.40 ± 6.92	32	1.5
	BOD_{in} (mg/L)			COD_{in} (mg/L)					
Summer	11.15 ± 4.93	27.06	3.10	20.76 ± 9.74	50.07	7.52			
Autumn	14.69 ± 2.29	18.84	10.59	33.72 ± 10.44	56.85	20.19			
Winter	24.62 ± 8.31	44.80	13.4	29.48 ± 4.19	38.16	19.44			

Table 2
Characteristics of effluent from NDPRP, showing the removal efficiencies

	pH_{out}			$P_{tot\ out}$ (mg/L)			SS_{out} (mg/L)		
	Ari. mean	Max	Min	Ari. mean	Max	Min	Ari. mean	Max	Min
Summer	6.36 ± 0.27	7.10	6.02	0.14 ± 0.05	0.21	0.10	4.89 ± 2.73	12.80	1.00
Autumn	6.22 ± 0.08	6.42	6.13	0.12 ± 0.07	0.03	0.26	4.92 ± 2.33	9.00	1.00
Winter	6.28 ± 0.10	6.49	6.13	0.21 ± 0.11	0.12	0.56	5.13 ± 2.30	12.00	1.20

	BOD_{out} (mg/L)			COD_{out} (mg/L)			Removal efficiency (%)			
	Ari. mean	Max	Min	Ari. mean	Max	Min	P_{tot}	SS	BOD	COD
Summer	5.40 ± 3.66	22.90	0.4	10.59 ± 6.37	32.13	1.9	87.07	61.27	52.51	49.37
Autumn	7.56 ± 0.92	9.74	6.11	16.83 ± 8.08	32.3	9.21	83.18	54.07	47.05	50.85
Winter	5.85 ± 3.72	14.7	0.8	16.05 ± 3.15	23.12	10.26	74.67	61.90	73.05	44.58

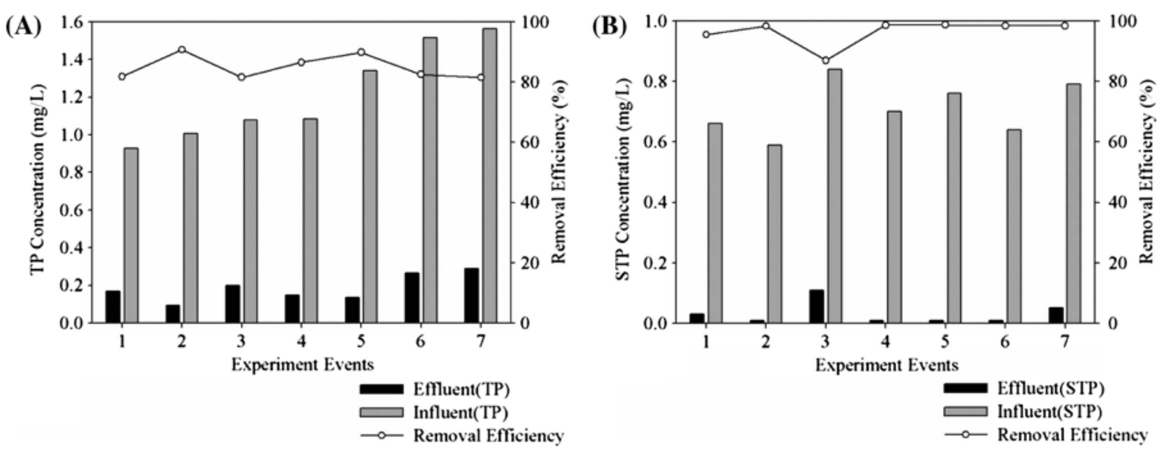

Fig. 4. Comparison of removal efficiencies between TP (A) and STP of inline static mixer (B).

The removal efficiency of COD was less than 50% due to characteristics of chemical precipitation [2]. For future studies, biological method could be used to increase removal efficiencies of COD [15].

3.2. Evaluation of system

3.2.1. Inline mixer

The quick and compact design approach could make it easy to set up the system and to treat a larger amount of wastewater (secondary effluent from a wastewater plant). In addition, it could give a high cost benefit from saving both the operating cost and the fixed cost. In order to design a quick-compact process, this study used an inline static mixer instead of a coagulation tank and coagulation-aid tank, which are widely used in the field of chemical precipitation [12]. Mean TP removal efficiency in the inline static mixer was 95.7% for STP and 85% for TP as shown in Fig. 4. These results indicate that the line static mixer has a high efficiency for eliminating soluble phosphorus. Since the inline mixer was designed primarily for rapid chemical reaction, and not for sedimentation,

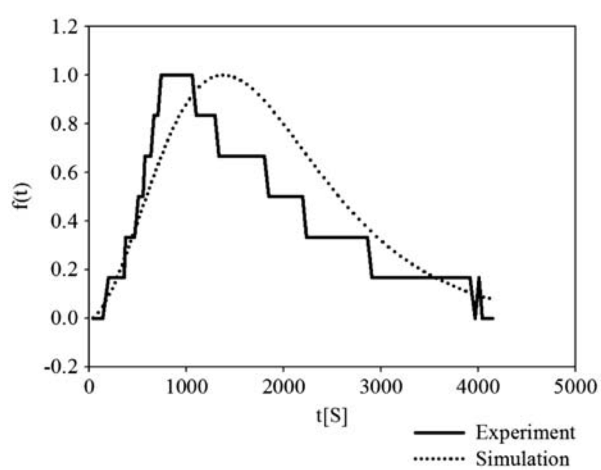

Fig. 5. Validation of RTD between experiment and simulation.

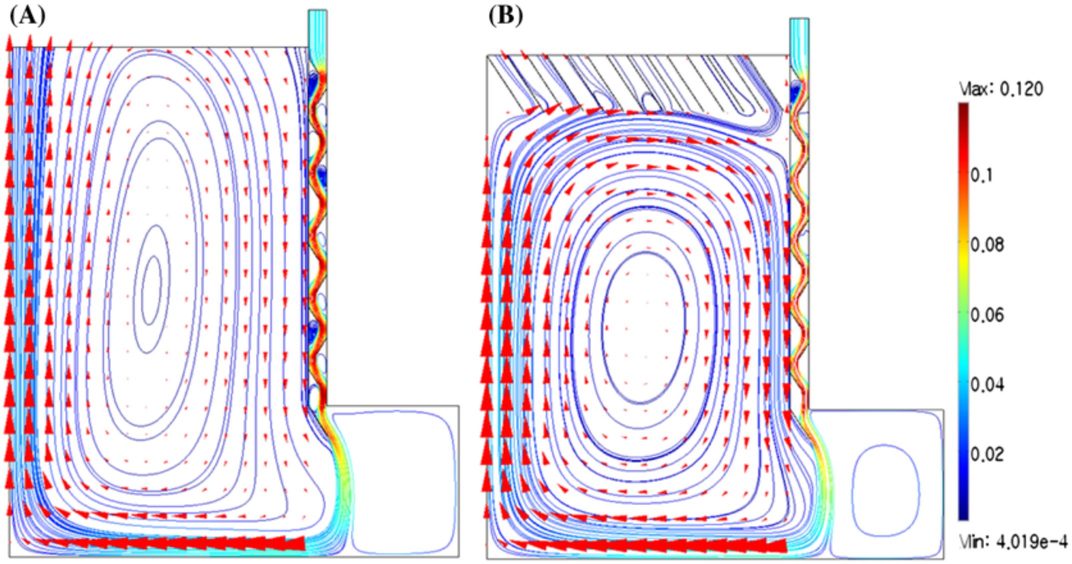

Fig. 6. Effect of inclined panel on stability of rising flow without inclined panel (A) and with inclined chamber (B).

relatively low particle removal efficiency would be expected. The total reaction time was only 1.2 s, which is significantly shorter than that for a conventional coagulation process (5 min) [12].

3.2.2. Sedimentation tank

To verify the 2D symmetric model, we compared the residence time distribution (RTD) results of experiment with simulation. For 2D model, convection/diffusion equation was applied to calculate the distribution of concentration with time. Fig. 5 shows that there was only 8% difference of RTD between the results of experiment and 2D symmetric numerical model. Therefore, the 2D symmetric model could fully reflect the actual sedimentation behavior in our studies.

The numerical model was applied to evaluate the performance of the sedimentation tank. For the optimal mixing intensity, an array of baffles was installed at the inlet of the sedimentation tank. Due to installation of these baffles, G value was calculated to be 53.11 [1/S] based on the Johnnes Haarhoff's studies [16]. Under the conditions of adding the inclined panel at the effluent part of a sedimentation tank and stable inflow rate, the flow pattern inside the tank did

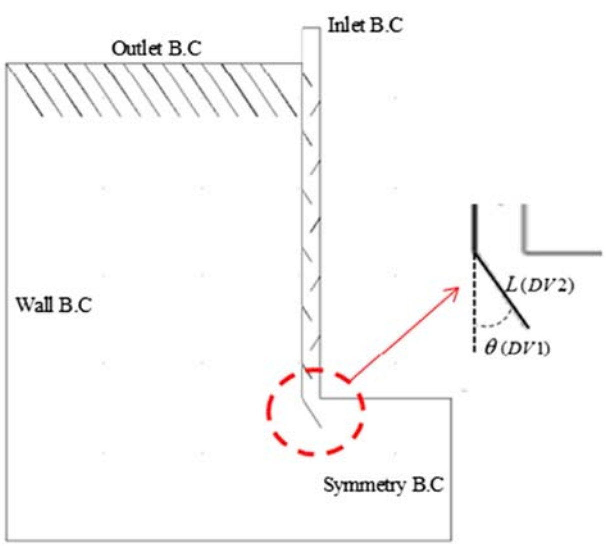

Fig. 7. DV, DV1: angle of guided baffle, DV2: length of guided baffle.

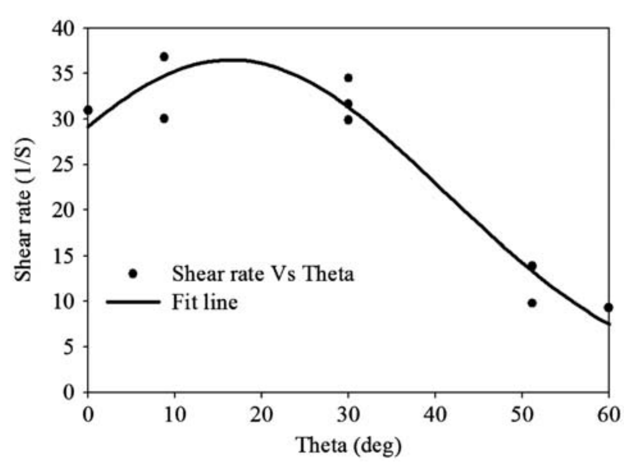

Fig. 8. Result of response surface, showing the relationship between angle of guided baffle and shear rate at the bottom of the sedimentation tank.

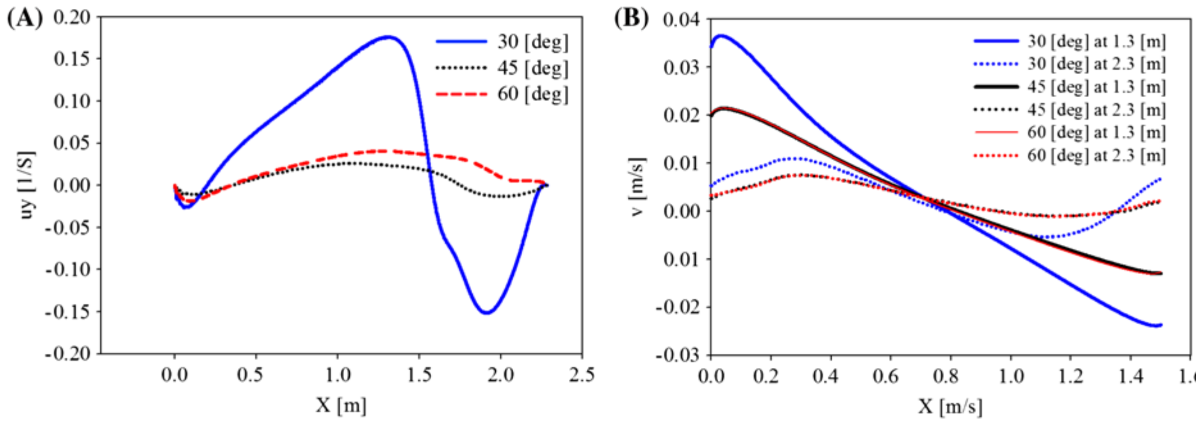

Fig. 9. Comparisons between the sedimentation performance among different angles of guided baffle (30˚, 45˚, and 60˚), (A) shear rate (B) rising velocity.

not tilt to one side. In addition, there was only one recirculation zone and the rising stable flow behaviors could be observed. The inclined panel could have contributed to the flow pattern inside the tank and made the flow behavior stable. As a result, we could observe the uniform distribution as seen in Fig. 6. The guiding baffle was another important parameter for sedimentation in the present study. As illustrated in Fig. 7, the guiding baffle changes the flow direction and flow rate at the bottom of the sedimentation tank to reduce the hydraulic energy, and hence, increase the sedimentation efficiency. Shear rate was another optimal factor for the sedimentation tank based on the value of theta, which is the critical parameter for optimal baffle design. Low shear rate at the bottom of the sedimentation tank would not only decrease the flow rate but also avoid breaking of the bottom sludge layer, preventing reduction in sedimentation efficiency of sludge. In addition, the shear rate and the rising rate of flow showed a strong interaction ($r^2 = 0.95$).

Optimal analysis was performed based on central composite design, which is one of the methods for Design of Experiment and Response Surface Method [17]. Length and angle of the guiding baffle were the design variables (DV) considered for determining the optimal design. However, as illustrated in Fig. 7, only the angle of guiding baffle showed interaction with the optimal design and thus was selected in the present research. Fig. 8 indicates that the theta (angle) of guiding baffle should be larger than 30˚ in order to reduce the shear rate. Moreover, Fig. 9 shows that the guiding baffles positioned in an angle of more than 30˚ helped to make a stable rising flow and low shear rate by effectively using the space at the bottom of the sedimentation tank. However, installation of very steep guiding baffle angle may generate a floc-breaking problem due to strong collision of both ways of flow. Therefore, avoiding a very steep angle (>60˚) is recommended.

3.3. *CSOs sludge application to the treatment of TP removal process*

3.3.1. *Quantification of first flush applying mass first flush (MFF) ratio*

During the rainy season, the cities with a combined sewer system face exceeding amounts of overflows from basin, drainage systems, and rivers. This event brings about diffuse contaminants, which depend on climate change and happen infrequently [18,19]. The first flush in the CSOs events contains major amount of pollutants. The amount of pollutants is the key parameters to evaluate the characteristics of CSOs event, because the first flush characterizes the function of the site and weather condition. The condition of site and weather is very important for bringing out the amount of overflows [20]. MFF ratio is used to quantify the magnitude of the first flush [21]. MFF describes the fractional mass of pollutants emitted as a function of the storm progress [20].

Table 3
MFF_{20} for events and parameters

Event no.	BOD	COD	SS	TN	TP
1	1.3	1.5	1.7	0.9	1
2	1.2	1.4	1.3	1.2	1.2
3	1.4	1.6	1.2	1.3	1.3
4	1.6	2.5	1	1.4	1.6
Average	1.4	1.8	1.2	1.2	1.3

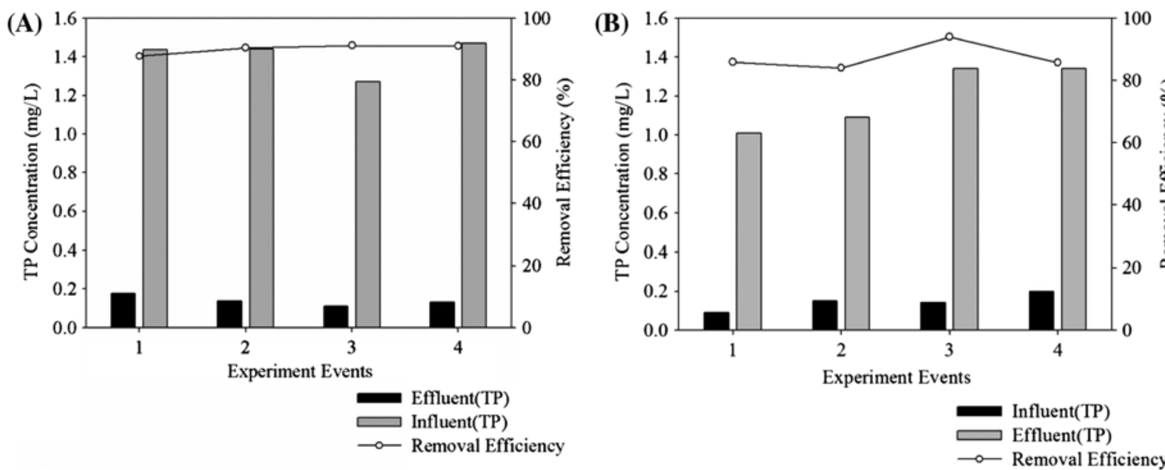

Fig. 10. Comparison of TP removal efficiencies between the treatment with CSO sludge (A) and the conventional treatment (B).

$$\mathrm{MFF}_n = \frac{\frac{\int_0^{T_1} c(t)q(t)\mathrm{d}t}{M}}{\frac{\int_0^{T_1} q(t)\mathrm{d}t}{V}} \quad (1)$$

In the equation above, n is the point in the storm, M is the total mass of emitted pollutants, V is the total runoff volume, $c(t)$ is the pollutant concentration, and $q(t)$ is the runoff volume as a function of time. If MFF is equal to 1, it indicates that there is no first flush. Table 3 shows the values of BOD, COD, SS, TN, and TP of the first flush based on MFF. It indicates that MFF value was low in event 1. This was probably due to small rainfall (18 mm) and thus a slightly high concentration of primary effluent. However, during a heavy rain event, the MFF value increased to 2.5 in COD. Overall, the first 20% of the runoff volumes contained 41% of pollutant mass.

3.3.2. CSOs sludge application

The conventional integrated waste water treatment plant is popularly applied in Korea [5] because it could deal with CSOs as well as wastewater treatment both in the wet and dry days. In the present NDPRP, we also performed integrated treatment. In events with rain, we normally used the NDPRP for cleaning the CSOs. If the rain stops, we also stopped the treatment to do the phosphorus removal. However, the main drawback of this procedure was that after each CSO treatment, the system is normally stopped to clean the CSO sludge, which takes time and increases the cost. In this work, an integrated treatment that applies CSO sludge to the TP treatment process without stopping the operations was studied. The recycling concentration of CSO sludge was 5,000 mg/L. Alum dosage was adjusted to be in the range of 2.5 ~ 3:1. Anionic polymer was used for the flocculation process. Without increasing the amount of reagents for phosphorus removal treatment, results indicated that the mean value of removal efficiency in the CSOs sludge recycling treatment was 90% (Fig. 10). These results indicate that CSO sludge being recycled for the TP removal treatment could lead to better removal efficiency than the conventional method with a mean removal efficiency of 85%. Zhou et al. [22] discussed that recycling sludge for the coagulation process can enhance pollutant removal. In this work, it was shown that recycling the sludge from CSOs significantly improved phosphorus removal efficiency under the same condition of chemical reagents and pH. Moreover, the coefficient of variance of the CSO sludge recycling treatment (CV = 0.01) was lower than that of non-CSO sludge recycling treatment (CV = 0.05), which means that the CSO sludge recycling treatment could lead to a stable removal result.

4. Conclusion

Based on the results of the research, the following can be concluded:

(1) Our findings suggest that the use of alum as the only coagulant coupled with an anionic polymer could give high removal efficiency of the phosphorus based on the NDPRP. However, this system only focused on reducing the phosphorus concentration in the effluent. To eliminate other pollutants, other processes would be necessary in future studies.

(2) The inline static mixer could effectively remove the STP (> 95% removal) and the sedimentation tank could give a stable hydraulic behavior for the higher particle sedimentation to remove the suspension solid. Our findings showed that the system, which combined the inline static mixer (for coagulation process) and the new baffle designed sedimentation tank, could lead to higher removal efficiency for phosphorus.
(3) The guiding baffle could effectively control the flow pattern to improve the sedimentation efficiency. CFD study of the sedimentation tank would be improved by applying hydraulic behavior analysis in the sedimentation. In addition, investigation of particle tracing and other unknown influencing parameters should be completed in future studies due to the complexity of the processes.
(4) It was also found that CSO sludge could possibly be applied to phosphorus removal process. Moreover, the new methodology can make the CSO-to-TP and TP-to-CSO nonstop treatment possible when used for the single phosphorus treatment plant.

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