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Development of a hybrid treatment system for combined sewer overflows using a hydrocyclone and a dissolved air flotation system

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ABSTRACT

Combined sewer overflows (CSOs) contain a mixture of untreated, contaminated sanitary, and storm water. CSOs include both precipitated and suspended matters. In this study, a novel system is proposed to treat CSOs using a combined hydrocyclone and dissolved air flotation (DAF) system for removal of both precipitated and suspended matter. The optimum operating conditions were determined by changing the internal flow rate and the split ratio (R_f) in the hydrocyclone and by changing the angle of the nozzle to determine the floc size, flow rate, and recycle ratio in the DAF system. The types of organic matter contained in prepared synthetic water samples are categorized as soluble COD_{cr} (SCOD) and particulated COD_{cr} (PCOD) in the characterization of the removal rate of the precipitated and suspended matter. The suspended solids (SS) were classified by their specific gravity to determine the removal rate of both precipitated and suspended matter. In a pretreatment process, the system employed a cationic polymer to obtain a low gradient time ($G \times t$) value. The results showed that poly-aluminum chloride (PAC) used with the cationic polymer had a 9.2% higher turbidity removal rate than PAC alone, due to a stable floc being achieved in the hydrocyclone. The optimum operating conditions of the hydrocyclone showed the highest efficiency at $R_f = 10\%$ at a flow rate of 2.8 m/s; the DAF-treated solutions showed a higher removal rate for SCOD solutions vs. PCOD solutions, with the highest turbidity removal rate of 65%. In contrast, when the hydrocyclone-treated solutions had a higher PCOD than SCOD, they showed a higher removal efficiency. The removal rates of SS, COD_{cr}, turbidity, T-P, and T-N of the total process were 77, 80, 98, 98, and 45%, respectively.

Keywords: CSOs; Dissolved air flotation; Floc size; Hydrocyclone; In-line static mixer; Strength factor

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1. Introduction

Combined sewer overflows (CSOs) contain a mixture of untreated, contaminated sanitary, and storm water [1]. The problem of contamination of receiving waters from overflows is as old as combined sewers themselves, but concerns have increased recently. The overflow load sent to the receiving water can be important and can have a major impact on the ecosystem [2].

The Ministry of Environment of the Republic of Korea have been in charge of maintaining water quality control to prevent such occurrences of water pollution [3] and a number of studies to control CSOs have been conducted in recent years [4–6]. In general, CSOs contain high concentrations of organic matter and suspended solids (SS). High hydraulic loading rates (HLRs) are required because of flows from massive storm water events. Technologies exist that can be used to treat CSOs, such as rapid precipitation [7] and hydrocyclones [8]. Dissolved air flotation (DAF) is also a technology that has a high turbidity removal capability and can cope with a high HLR [9], as it is possible to flocculate particles using a coagulation process to treat CSOs, and soluble organic compounds can be removed from solution [10]. Conventional coagulation/flocculation processes require a large area and a long retention time to coagulate a large mass from a CSO, but the use of an in-line static mixer can shorten the time required and can simplify the process for rapid coagulation [11].

A hydrocyclone is a type of hydrodynamic separator that was first developed by Bretney in 1891 and is now widely used in several fields [12,13]. The theory of operation is to separate particles as a solid or liquid using centrifugal force, and a high HLR operation is possible. In addition, there are no moving parts and hydrocyclones are cheap to operate with low management/maintenance overheads [14,15]. Hydrocyclones are especially effective for the removal of fine particles and are used for this purpose in many industries. Although hydrocyclones can rapidly treat CSOs, which contain settleable SS and particles, the problem of nonsettleable SS and organic matter remains [16].

DAF systems have advantages in particle removal and are able to remove suspended matter effectively. Moreover, they can remove only some pollutants, including dissolved matter, efficiently and they are easy to maintain [9]. In this study, we aimed to: (1) optimize the floc size of an in-line static mixer; (2) determine the operational conditions using a hydrocyclone for the flow rate and R_f; and (3) develop a hybrid treatment system to reduce suspended matter by combining a hydrocyclone and a DAF system to treat high CSO volumes with high contaminant concentrations.

2. Materials and methods

2.1. Preparation of synthetic CSO samples

The synthetic CSO samples used in this study were prepared as shown in Table 1, based on data reported from previous studies. A carbon source was prepared using peptone (Acumedia Manufacturers Inc. MI, USA), a bacto-yeast extract (Difco, MI, USA), $CH_3COONa_3H_2O$ (Daejung Chemicals, Korea), and sawdust (<600 μm). The SS were mixed with kaolin (Daejung Chemicals), clay (<600 μm), and sawdust. T-N and T-P samples were prepared comprising NH_4Cl (Daejung Chemicals) and K_2HPO_4 (Daejung Chemicals), respectively. The pH and temperature of the solutions were adjusted to 7 ± 0.5 and 25 ± 2˚C, respectively.

2.2. Schematics of the system

As shown in Fig. 1, along with a coagulant as poly-aluminum chloride (PAC) silicate and a cationic polymer (C-810 EB, OCI-SNF Company Ltd.), the synthetic CSO samples were simultaneously injected into an in-line static mixer fed by a pump. The in-line static mixer had dimensions of length = 10 cm and diameter = 2 cm and had six elements. The hydrocyclone was designed using the parameters shown in Table 2 to treat any particles present in the solutions and to precipitate any organic matter. The DAF process removed any fine particles and suspended organic matter that were not removed by the hydrocyclone. The pressure of the saturation tank and the recycling rate of the DAF were 5 atm and 17%, respectively. A bubble nozzle was fixed in the upflow direction. The volume of influent was controlled using a valve located on the upper side of the hydrocyclone inlet, and the retention time was measured by changing the pipe diameter at the retention time change point. The total electric power consumed was calculated using Eq. (1) employing a pressure gage:

$$P = \gamma Q h \tag{1}$$

where P is the electric power (kW), γ is the unit weight of water (kN/m^3), Q is influent flow (m^3/s), and h is the head loss (m).

G value of in-line static mixer can calculate as substituted Eq. (1) into Eq. (2).

Table 1
Synthetic source water in other research

Analyses	This research	Choi et al. [17]	Kim et al. [18]		Sin et al. [19]	Seo et al. [20]
Turbidity (NTU)	800 ± 50	–	–	–	–	–
BOD_5 (mg/L)	–	626	163	159.8	128	686
COD_{cr} (mg/L)	800 ± 20	–	770	102	757	1,100
SS (mg/L)	1,600 ± 50	895	528	95.2	162	2,366
T-N (mg/L)	16 ± 2	–	56.5	37.4	28.5	102
T-P (mg/L)	4 ± 2	–	1.9	7.3	3.26	37.1

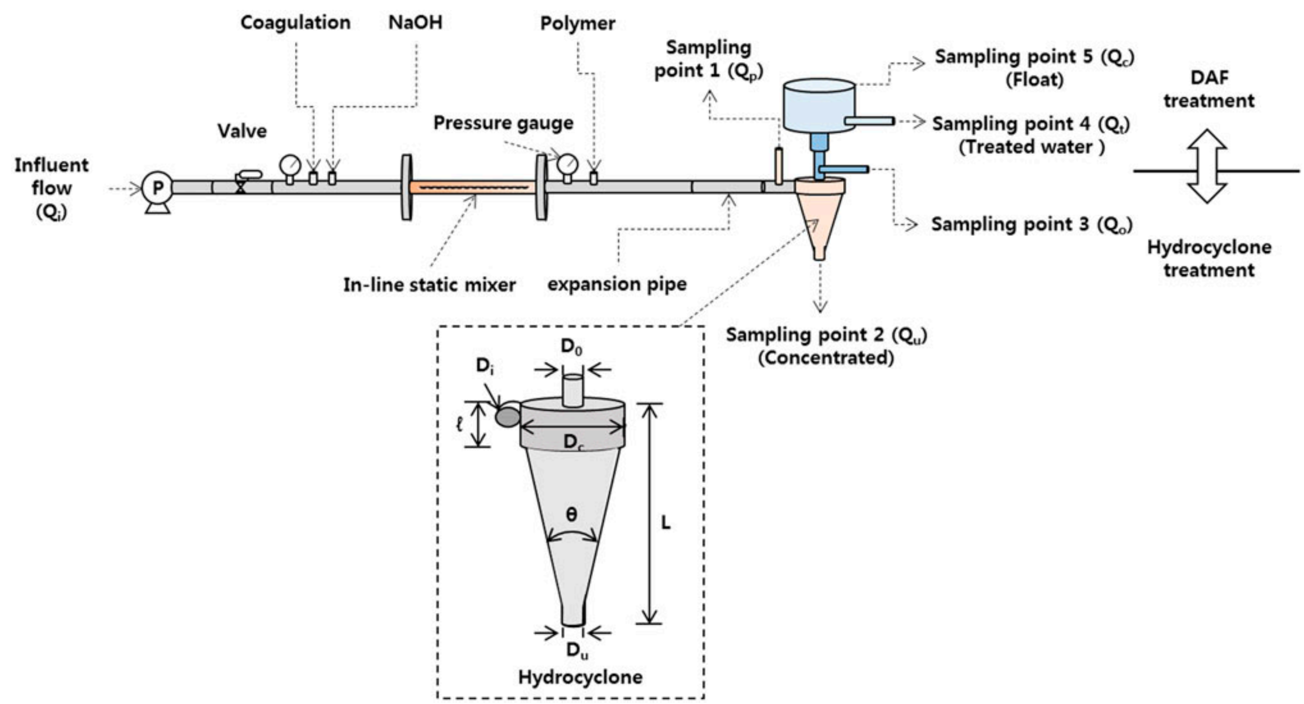

Fig. 1. Schematic drawing of the system.

Table 2
Geometry of the hydrocyclone in this study

D_i/D_c	D_0/D_c	ℓ/D_c	L/D_c	Angle θ	D_c	Inlet
0.224	0.345	0.3445	3.448	13	0.058	Involuted feed

$G \times t$ also can calculate multiplied by residence time (t).

$$G = \sqrt{\frac{p}{\mu \times V}} \tag{2}$$

where G is gradient (sec^{-1}), μ is the viscosity of the liquid (Pa s), V is in-line static mixer volume (m^3).

2.3. Optimum dose of coagulant

The optimum coagulation conditions were determined by rapidly mixing the solutions at 150 rpm for 15 min and then slowly mixing the solutions at 40 rpm for 30 min using a jar tester (Phipps & Bird, USA), followed by measuring the turbidity using a turbidity meter (Model URBI200ND, Hach Co., USA). PAC was used as a coagulant and was injected in concentrations of 1, 2, 4, 6, 8, and 10 mg Al/L. The optimum coagulant dose was determined at the in-line mixing stage. In addition, to prevent degradation of the floc inside the hydrocyclone, the coagulation strength was enhanced by injecting a cationic polymer in concentrations of 1, 2, 4, 6, 8, and 10 mg/L. The coagulant and cationic polymer dosing range determined from the jar test apparatus results was then coinjected using a pump at a flow rate of 20 L/min into the in-line static mixer. NaOH used for pH adjustment. Along with the PAC, a cationic polymer and a 2 M NaOH solution were pumped into the system using a master flux pump (SK Science Co.).

2.4. Analysis of the floc strength and turbidity

To identify the effect on the turbidity and the strength of the coagulated floc of the hydrocyclone and DAF process, samples taken at four sampling points (Q_i, Q_p, Q_u, and Q_o) were analyzed (Fig. 1). The size of the floc was analyzed using a particle size analyzer (Mastersizer 2000, Malvern Instruments, UK). The average D_{50} value from the particle analyzer was defined using Eq. (3).

$$d = 2\sqrt{\frac{P}{\pi}} \tag{3}$$

where d is the floc size (μm) and P is the circumference of D_{50} (μm). The strength of the floc was determined from the measured d values and Eq. (4).

$$\text{Strength factor} = \frac{d(2)}{d(1)} \times 100 \tag{4}$$

where $d(1)$ is the floc size (μm) before particle destruction and $d(2)$ is the floc size (μm) after particle destruction. The floc size before particle destruction was measured at Q_i and Q_p, and the floc size after particle destruction was measured at Q_u and Q_o. The analysis of the particle strength was conducted by comparing the change in strength by measuring the turbidity after particle destruction and then again after a period of 30 min.

2.5. Retention time of the in-line static mixer

An increase in particle size was induced by increasing the retention time achieved by positioning an expansion pipe in the latter part of the in-line static mixer. The length of the expansion pipe shown in Fig. 1 was 300 mm. After changing the pipe diameter from 23, 33, 40, to 52 mm, the relationship between the removal of turbidity and the floc size of the effluent was determined.

2.6. Operating conditions of the hydrocyclone

R_f is a major operational factor that is determined by the split ratio (Q_u/Q_i) of the influent flow (Q_i) of the hydrocyclone and the concentrated (Q_u). The optimum value of R_f, determined from the turbidity removal and floc size, depended on the discharge value, being 4, 6, 8, 10, and 12% of the influent flow (Q_i). The flow rate inside the hydrocyclone was directly dependent on the velocity and the Reynolds number. The turbidity removal rate was analyzed using Eq. (5) while changing the flow rate from 1.5, 1.9, 2.4, 2.8, to 3.4 m/s:

$$\text{Re} = \rho D_c v/\mu \tag{5}$$

where ρ is the density of the liquid (kg/m^3), D_c is the diameter of the swirling chamber (m), v is the velocity of the hydrocyclone (m/s), and μ is the viscosity of the liquid (Pa s).

2.7. Particle removal vs. SG

Since CSOs contain precipitated solids and suspended matter, in this study, the SS removal rate of the hydrocyclone and DAF process was monitored using different particles with two different SG values. One particle used was sand with a specific gravity of SG = 2.1; the other particle used was sawdust with a specific gravity of SG = 0.2. Three types of solution were prepared with particles in the range 150–300, 60–150, and 30–60 μm in a concentration of 10 g/L in distilled water. The SS removal efficiency was measured after each type of particle was injected into the system.

2.8. SCOD and PCOD removal

CSOs contain organic matter, such as SCOD and PCOD, and the characteristics of the synthetic water (SW) samples used to model these are shown in Table 3. The COD_{cr}, T-N, T-P, and turbidity values were analyzed using a kit analysis method (Humas Co., Korea) using a spectrophotometer (Model DR5000TM, Hach Co., USA).

3. Results and discussion

3.1. Optimum condition of coagulation

Fig. 2 shows the results of the turbidity measurements in the case of using PAC and a cationic

Table 3
SW characteristics of the SCOD and PCOD

Item	Characteristics
SW-1 (SCOD 100%)	Organic matter = peptone, bacto-yeast extract, and $CH_3COONa_3H_2O$
	Turbidity = kaolin and clay
	T-N = NH_4Cl
	T-P = K_2HPO_4
SW-2 (SCOD 50% + PCOD 50%)	Organic matter = peptone, bacto-yeast extract, $CH_3COONa_3H_2O$, and sawdust
	Turbidity = kaolin, clay, and sawdust
	T-N = NH_4Cl
	T-P = K_2HPO_4
SW-3 (PCOD 100%)	Organic matter = sawdust
	Turbidity = kaolin, clay, and sawdust
	T-N = NH_4Cl
	T-P = K_2HPO_4

polymer that were injected individually or as a mixture into the in-line static mixer. Use of the in-line static mixer showed a lower turbidity efficiency than the jar test results. The turbidity using a PAC solution at a concentration of 6 mg Al/L decreased from 800 to 110 NTU, and a value of 11.6 NTU was obtained using a cationic polymer concentration of 4 mg/L, which was only 9.2% higher than the value obtained using a PAC additive to the solution. The mixing intensity of the in-line mixer was 5,291 s^{-1}, which is higher than that achieved by rapidly mixing a solution (150 s^{-1}), and slowly mixing in a jar test (30 s^{-1}). However, on considering the mixing time (t), the in-line static mixer achieved mixing within a period of 1 s, while the jar test achieved mixing within 900 s and 1,800 s. The $G \times t$ values were 40 times higher than the jar test values. This caused a reduction in the mixing intensity of the in-line static mixer. To account for this, we placed an expansion pipe in the latter part of the mixer. Coinjecting the cationic polymer also helped to achieve a similar efficiency to the jar test.

3.2. Turbidity, floc size, and strength factor vs. pipe diameter

Fig. 3 showed the effect of floc size on the extended retention time when using the expansion pipe as shown in Fig. 1. It is reported that the floc sizes increased according to retention time in the flocculation basin [21]. This shows that the turbidity and floc size of the treated water samples depended on the pipe diameter placed in the in-line static mixer. The floc size increased with increasing diameter of the expansion of pipe, until it reached its final value of 18 μm. The increased floc size influenced the turbidity removal rate of the hydrocyclone. The enhancement observed when using a cationic polymer was not degraded in the high velocity of the hydrocyclone.

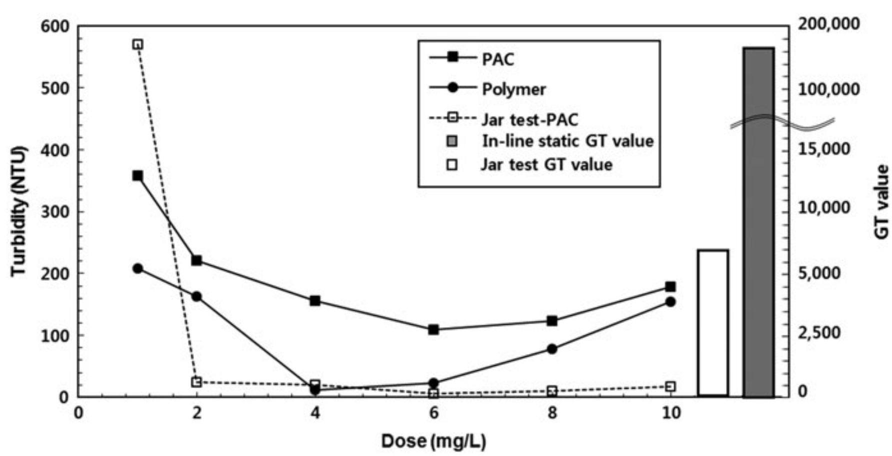

Fig. 2. Turbidity depending on dosage of coagulants.

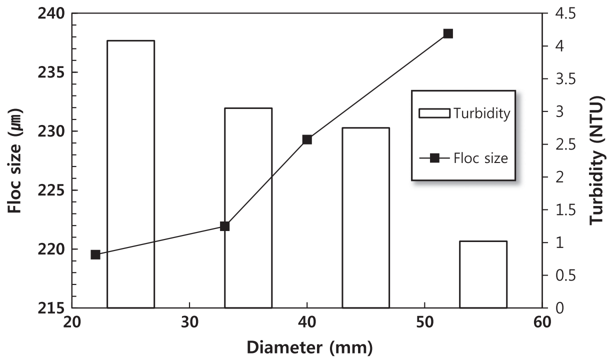

Fig. 3. Variation of turbidity and floc size depending on pipe diameter.

3.3. Turbidity and strength factor in the hydrocyclone depending on coagulant

Fig. 4 showed the results of turbidity and strength factor vs. coagulant at the hydrocyclone. The lowest turbidity rate observed was 6 mg Al/L in the case of PAC coinjection only, with the highest turbidity value observed being 10 mg Al/L. Without the use of the cationic polymer, the strength factor was as high as 100 before the hydrocyclone and gradually reduced to a value of 29 after the hydrocyclone. In contrast, a constant strength factor value of 100 was maintained after the hydrocyclone on coinjecting a solution containing the cationic polymer as shown in Fig. 5. This is because the floc size was easily destroyed under the high shear stress in the hydrocyclone [22]. A low mixing intensity in the hydrocyclone would increase the floc size, if it could play the role of a slow mixing chamber [23]. This result shows that injecting coagulant alone can lead to a rapid decrease in the floc size from the shear stress, while coinjecting with a cationic polymer leads to an increase in the floc size because of the high strength factor in the hydrocyclone. Therefore, coinjecting with a cationic polymer is required when using a hydrocyclone to prevent the destruction of the floc aggregates.

3.4. Optimum operating conditions of the hydrocyclone

R_f is a major operating parameter that determines the efficiency while operating a hydrocyclone. The value of R_f can be determined from the ratio of the influent flow (Q_i) and the concentrated (Q_u). In general, an increase in Q_u leads to an increase in the operating efficiency, and a decrease in Q_u leads to a decrease in the operating efficiency. However, an excessive increase in the Q_u will lead to a reduction in the volume of treated water, so an appropriate value of R_f is important [24]. Fig. 6 shows the value of R_f determined by controlling the volume of Q_u for a Q_i. At $R_f = 4\%$, a low turbidity removal efficiency rate was achieved. The highest turbidity removal efficiency rate of 83% was observed for a value of $R_f = 10\%$.

Fig. 7 shows the dependence of the turbidity removal efficiency on the Reynolds number. When the Reynolds number was 21,000, the highest removal efficiency observed was at 72%. This was explained from the increased flow rate, which enhanced the centrifugal force, and thus, led to an increase in the value of R_f. However, when the flow rate increased further, the retention time in the hydrocyclone decreased, and thus, the turbidity removal efficiency also decreased from the effect of a short-circuiting of the flow.

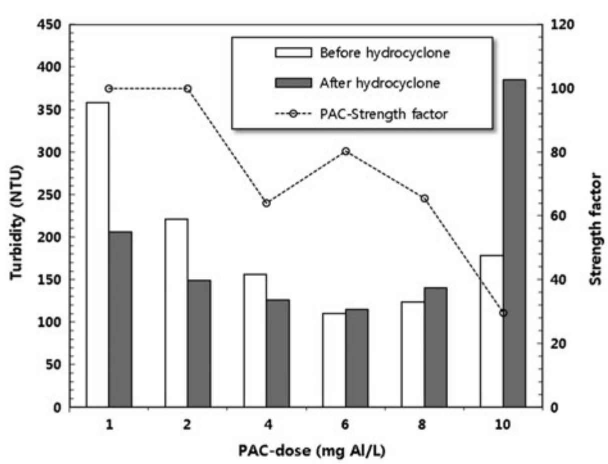

Fig. 4. Variation of turbidity and strength factor of the coagulant dose before and after the hydrocyclone.

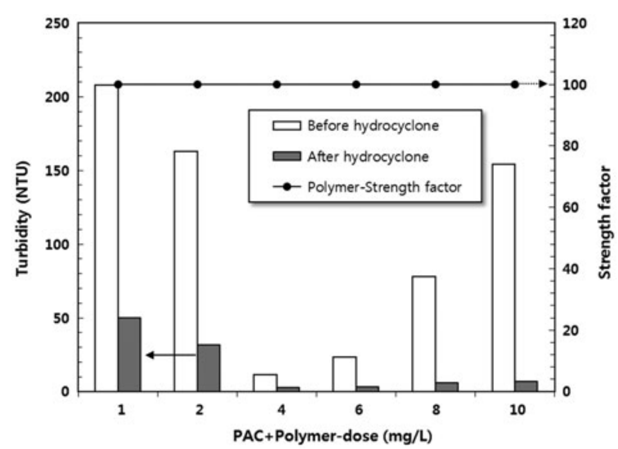

Fig. 5. Variation of turbidity and strength factor of the cationic polymer dose before and after the hydrocyclone.

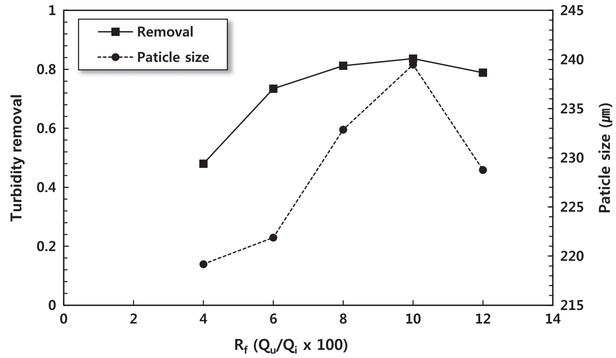

Fig. 6. Relationship between the turbidity, particle size, and R_f.

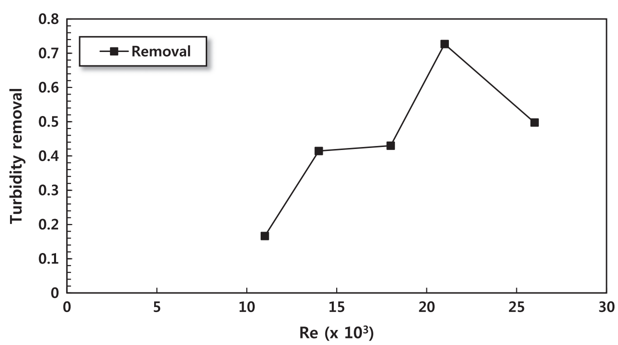

Fig. 7. Variation of turbidity removal rate depending on the Reynolds number.

3.5. SS removal efficiency of the hydrocyclone and DAF process using the SG of particles

Fig. 8 shows the SS efficiency of sand (SG = 2.1) and sawdust (SG = 0.2) removed by the hydrocyclone and DAF process. The sand was precipitated effectively by gravity and mostly settled inside the hydrocyclone. Precipitation using centrifugal force was more effective than using upflow. The hydrocyclone removed an average of 80% of the sand, while the DAF removed an average of 20% of the sand. However, as the particle size of the sand decreased, it was removed more efficiently by the DAF process than by the hydrocyclone. In the case of sawdust removal, the hydrocyclone and DAF showed average efficiencies of 43 and 57%, respectively. However, larger particle size sawdust (150–300 μm) had a removal efficiency of 70% using the hydrocyclone.

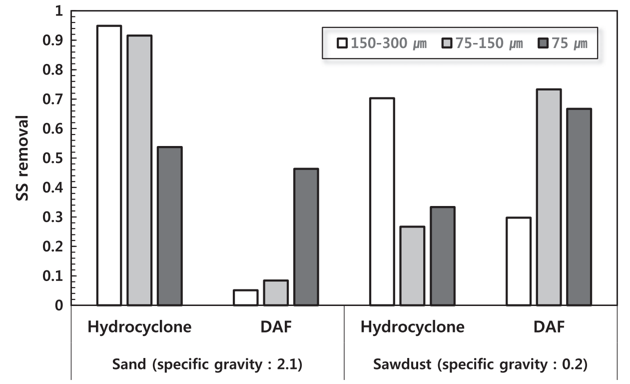

Fig. 8. SS removal rate of the hydrocyclone and DAF depending on SG.

3.6. Results of average water quality from the effluent at each sample point

Table 4 shows the SS, turbidity, COD_{cr}, T-N, and T-P removal from the effluent at each process stage using the three types of SW samples. The removal of SS and organic matter was high, because matter with a high SG, such as clay, kaolin, and sawdust, was mainly removed by the hydrocyclone. The DAF process played a role in reducing the SS and organic matter that was not fully removed by the hydrocyclone, which was especially true for the lighter materials contained in the inflow. The COD_{cr} value of sample SW (SW-1) showed it had been removed by up to 75% by the hybrid system, while it had a removal efficiency of 65% using the DAF process alone. When sample SW-2 was treated with the hydrocyclone, it showed a higher removal rate of the SS and organic matter than sample SW-1. In sample SW-3, an agglomeration of the sawdust, clay, and kaolin from using the coagulant and the cationic polymer allowed the particles to settle effectively. As a result, sample SW-3 showed a higher removal efficiency than sample SW-2, because 73% of the SS and organic matter was removed by the hydrocyclone. The removal rate of the SS and organic matter using the hydrocyclone was high for insoluble matter. However, in terms of turbidity, the DAF process showed a high removal efficiency of 96–97%. Since sawdust was used as the insoluble organic matter, and it has a low SG, it showed excellent precipitation rates using the hydrocyclone. From the results of our tests, the removal of dissolved matter was better achieved using the DAF process than using the hydrocyclone, but the

Table 4
Average water quality of the effluent at sampling points

Sample point	Synthetic water sample	Turbidity (%)	SS (%)	COD_{cr} (%)	T-N (%)	T-P (%)
Q_{final}	SW-1	98	70	75	44	99
	SW-2	98	76	78	40	98
	SW-3	99	85	88	50	97
Q_u	SW-1	<0.1	<0.1	<0.1	2	<0.1
	SW-2	<0.1	<0.1	<0.1	<0.1	<0.1
	SW-3	<0.1	< 0.1	<0.1	2	<0.1
Q_o	SW-1	58	27	29	40	63
	SW-2	63	52	52	34	30
	SW-3	69	73	73	38	30
Q_c	SW-1	<0.1	<0.1	19	<0.1	<0.1
	SW-2	<0.1	<0.1	<0.1	1	3
	SW-3	<0.1	<0.1	<0.1	2	<0.1
Q_t	SW-1	97	58	65	7	97
	SW-2	96	49	53	9	97
	SW-3	96	45	54	19	95

removal of insoluble matter showed the reverse, namely using the hydrocyclone was better than using the DAF process. The T-P removal rate was 97–99% using precipitation and flotation, which are physical treatments rather than chemical treatments.

4. Conclusions

A cationic polymer was required to be coinjected at the in-line static mixer to enhance the coagulation/flocculation processes for low $G \times t$ values. PAC used with the polymer had 9.2% higher turbidity removal rate than PAC alone, due to a stable floc being achieved in the hydrocyclone. Optimum coagulation efficiency, the retention time increased on changing the diameter of the pipe, and the floc size increased to 18 μm. When $R_f = 4\%$, the turbidity removal efficiency was low, but an 83% removal efficiency was achieved when $R_f = 10\%$. When the Reynolds number was 21,000, the highest removal efficiency observed was at 72%. This was explained from the increased flow rate, which enhanced the centrifugal force, and thus led to an increase in the value of R_f. The hydrocyclone showed an average sand removal efficiency of 80% while the DAF showed an average sand removal efficiency of 20%. However, as the particle size of the sand decreased, it was removed more efficiently by the DAF process than by the hydrocyclone. In the case of sawdust removal, the hydrocyclone and DAF showed an average removal efficiency of 43 and 57%, respectively. The COD_{cr} value of sample SW-1 showed a removal efficiency of 75% using the hybrid system, while a removal efficiency of 65% was achieved by the DAF process alone. When sample SW-2 was treated using the hydrocyclone, it showed a higher removal efficiency of the SS and organic matter than sample SW-1. Sample SW-3 showed a higher removal efficiency than sample SW-2, because the SS and organic matter showed a removal rate of 73% using the hydrocyclone.

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