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Abstract: Many reservoirs have been constructed in Korea to store water resources utilizing the terrain of the land. In general, dam source waters contain algae species that have densities close to that of water. Consequently algae are difficult to remove by conventional gravity sedimentation (CGS), while dissolved air flotation (DAF) is known to be an effective process for the purpose. The same source waters usually also have high turbidities due to mineral soil particles in the wet summer season. Systematic studies on the effect of high turbidity on the DAF process are very limited. In this work, DAF and CGS experiments were carried out to investigate water treatment characteristics and removal efficiencies under various COD/SS and chlorophyll-a/SS ratios. A kinetic DAF process model was employed to describe bubble-floc collision

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and agglomeration, as well as the rising velocity of bubble-floc agglomerate. Our results showed that the initial collision-attachment efficiency for the clay floc size range of 100−400 μm was a relatively low value of 0.3. The removal efficiency by DAF was greater than by CGS when chlorophyll-a/SS ratio was high. It was also found that sedimentation prior to flotation is required for the effective separation of large clay flocs caused by runoff. Our experimental and theoretical results also suggest that the DAF process requires carefully operation in Korea, especially, in the rainy summer season.

Keywords: Dissolved air flotation, rainfall, inorganic particles, sedimentation, water treatment

INTRODUCTION

Many reservoirs have been constructed in Korea to store water resources, utilizing the terrain of the land. Dam source waters generally contain many algae species that have densities close to that of water, does not settle readily or tend to float. Many conventional water treatment plants in Korea using gravity settling used to experience serious operational problems due to the presence of algae (1).

Dissolved air flotation (DAF) is known as an effective solid/liquid separation process for low-density particles, and is an popular process for the conventional gravity sedimentation (CGS) in Northern Europe water treatment practice. DAF units comprise four subprocesses: (1) coagulation and flocculation prior to flotation (2), bubble generation (3), bubble-floc collision and attachment in a mixing zone, and (4) rising of bubble-floc agglomerates in a flotation tank. (2) DAF proved to be a superior process for treating algae laden waters with low turbidity (3–7). Thus, it has been successfully applied in Korea to deal with algae blooms that occur frequently in euthrophized source waters. Recently, several large water treatment plants such as the Wonju plant (230,000 m^3/day) and the southern Jeonnam plant (200,000 m^3/day) adopted the DAF process.

Dam waters also can have high turbidity due to runoff loaded with inorganic particles. Therefore, the water characteristics of almost all reservoirs depend on both inorganic load due to runoff and phytoplankton load caused by nutrient. Hence the simultaneous removal of both inorganic and algal particles is frequently required during the rainy season in Korea. Although DAF units have been successfully applied to treat algae-laden water with low turbidity, systematic studies of the effect of high turbidity of inorganic particles caused by rainfall on DAF process are very limited. Recently, Kwak (1) suggested that the presence of inorganic particles highly affects the flotation efficiency.

In this work, particle separation efficiency was examined using a DAF pilot plant at a conventional water treatment plant during the rainy season. In addition, the influence of inorganic particles on the DAF process was investigated under various COD/SS and chlorophyll-a/SS ratios. A population balance model for the DAF process was employed to describe the bubble-floc collision and their agglomeration.

THEORETICAL APPROACH

The population balance for describing the process of bubble-floc collision and attachment was formulated by counting the number of flocs with attached i bubbles, $n_{f,i}$ within an elapsed time of mixing, t. Based on the assumptions reported by Fukushi (3), the governing equations are given as follows [Eqs. (1–6)].

$$\frac{dn_{f,i}}{dt} = \frac{3}{2}\pi\beta\sqrt{\frac{\varepsilon_0}{\mu}}n_a(d_a + d_f)^3(\alpha_{f,i-1}\cdot n_{f,i-1} - \alpha_{f,i}\cdot n_{f,i}) \quad (i = 1 - m_f) \tag{1}$$

The population balances for flocs with no air bubble attachment and for free bubbles are given by Eqs (2) and (3).

$$\frac{dn_{f,0}}{dt} = \frac{3}{2}\pi\beta\sqrt{\frac{\varepsilon_0}{\mu}}n_a(d_a + d_f)^3(-\alpha_{f,i}\cdot n_{f,0}) \quad (i = 0) \tag{2}$$

$$\frac{dn_a}{dt} = -\int_0^{\infty}\left\{\frac{3}{2}\pi\beta\sqrt{\frac{\varepsilon_0}{\mu}}n_a(d_a + d_f)^3\sum_{i=0}^{m_f-1}(\alpha_{f,i}\cdot n_{f,i})\right\}dd_f \tag{3}$$

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The maximum attachable number of bubbles (m_f) on a certain size of floc (d_f) can be written as:

$$m_f = \pi\alpha_0(d_f/d_a)^2 \tag{4}$$

The collision-attachment factor (α) is determined by the coverage of cationic precipitated coagulant on a floc surface and the number of attached bubbles are given by

$$\alpha_{f,i} = \alpha_{f,0}(1 - i/m_f) = \alpha_0(1 - i/m_f) \tag{5}$$

By introducing dimensionless variables (see nomenclature) and applying Laplace transformation methods, the number of F-size flocs with i bubbles can be represented as follows (8):

$$N_{F,i} = {}_{m_F}C_i\cdot\exp\{1-(1+F^3)\theta\}\cdot\left[\left\{\exp(1+F^3)\frac{\theta}{m_F}\right\} - 1\right]^i \quad (i = 0 - m_F) \tag{6}$$

Here, $_{m_F}C_i$ is the mathematical combination of m_F and i. By inserting the attached bubble flotation and floc density functions into Stoke's equation, the rise velocity (W_{af}) of bubble-floc agglomerate is given by Eq. (7).

$$W_{af} = \frac{4g}{3\mu k}\cdot\frac{i(\rho_w - \rho_a) - a(d_f/1)^{-Kp}(d_f/d_a)^3}{i + (d_f/d_a)^3}\cdot d_{af}^2 \tag{7}$$

Here, the diameter of the floc-bubble agglomerate (d_{af}) and the drag force constant (k) are calculated using Eqs (8) and (9).

$$d_{af} = (d_f^3 + id_a^3)^{1/3} \tag{8}$$

$$k = \frac{16id_a^2 + 45d_f^2}{id_a^2 + d_f^2} = \frac{16i + 45(d_f/d_a)^2}{i + (d_f/d_a)^2} \tag{9}$$

The explanation of other parameters is presented in the nomenclature section.

METHODS AND MATERIALS

The schematic diagram of the DAF pilot plant is shown in Fig. 1. For the comparison of the solid removal efficiency between DAF and CGS, sedimentation experiments were conducted for the SJK (Sumjinkang, Korea) water treatment plant (75,000 m^3/day), and flotation experiments were performed using a semi-field scale DAF pilot plant (1.0 m^3/hour). Feed water for the DAF pilot plant experiment was taken from the rapid mixing chamber of the SJK water treatment plant (Fig. 1). The water quality is listed in Table 1. Sedimentation and DAF experiments using water from the SJK water treatment plant were conducted according to the conditions listed in Table 2. In the DAF

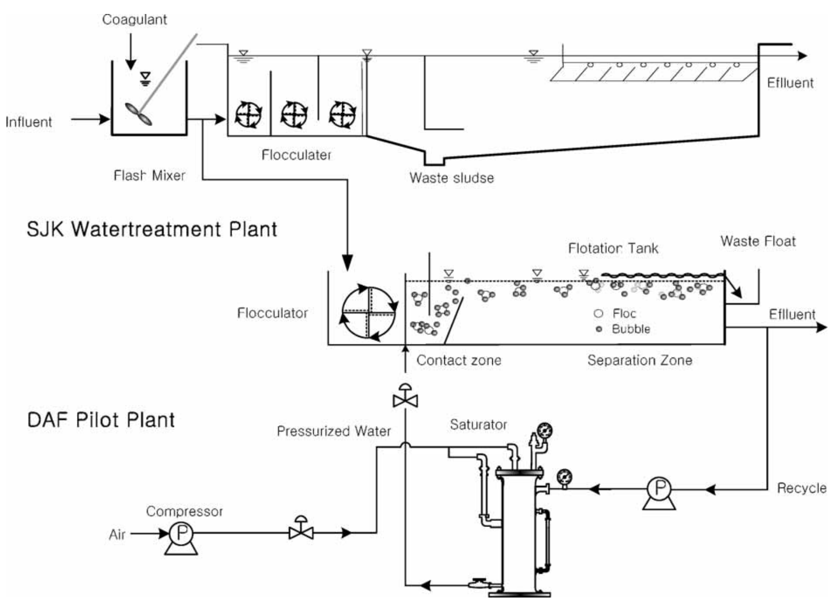

Figure 1. Schematic diagram of DAF pilot plant and the SJK water treatment plant.

Table 1. Water quality of SJK water treatment plant

Item	Value
pH	6.8–7.2
Turbidity (NTU)	2.0–20.0
Alkalinity (mg/l as $CaCO_3$)	10.0–30.0
BOD (mg/l)	1.5–2.0
COD (mg/l)	2.0–3.0
Consumption of $KMnO_4$ (mg/l)	6.0–12.0
SS (mg/l)	1.8–2.5

process, the influent descended behind a baffle and entered the contact zone through a slot at the bottom. Subsequently, the water was first flowed upward and then horizontally over the shaft wall, and entered the separation zone. Several dissolved air flotation and gravity sedimentation experiments were carried out in a batchwise manner to obtain the particle characteristics, using a vertical column (height 1,800 mm, diameter 150 mm) under the same operational conditions as existed in continuous treatment. To simulate high turbidity by mineral particles, synthetic clay was spike dosed into the raw water at SKJ. The chemical composition of the clay is shown in Table 3.

Table 2. Operation parameters of SKJ WTP and DAF pilot plant

Unit process	Description	CGS (SKJ WTP)	DAF (pilot plant)
Flash mixing chamber	Mixing time	3–4 min	2–3 min
	Mixing speed	135 rpm	150 rpm
	G	650 sec^{-1}	700 sec^{-1}
Slow mixing chamber	Mixing time	30–40 min	20–30 min
	Mixing speed	45 rpm	50 rpm
	G	35, 50, 65 sec^{-1}	60 sec^{-1}
Flotation basin	Contact time		3–4 min
	Angle of baffle		60°
	Separation time		20–30 min
	Surface loading		3.5–4 m/h
Sedimentation basin	Sedimentation time	3.5–4 h	
	Surface loading		
Chemicals	Coagulant	Poly aluminum chloride	Poly aluminum chloride
	Dose of coagulant	15–30 ppm	15–30 ppm
	Alkalinity agent	$Ca(OH)_2$	$Ca(OH)_2$
	Dose of $Ca(OH)_2$	10–20 mg/L	10–20 mg/L

Table 3. Chemical composition of clay

Composition	Contents (%)[a]
SiO_2	46
Fe_2O_3	2
Al_2O_3	35
CaO	3
Etc.	14

[a]Analyzed by XRF.

RESULTS AND DISCUSSION

COD/SS and Chlorophyll-a/SS Ratios of Raw Water

Korea's Ministry of Environment measured raw water parameters periodically, including pH, DO, BOD, COD, SS, T-N, T-P, and coliform group, etc., to monitor water quality changes in reservoirs. Although there are many criteria indicating the raw water quality in drinking water treatment, COD and SS have been widely accepted as sutogates of organic and inorganic concentrations, respectively. Thus, the ratio of COD/SS could be broadly used in determining whether the given water contains high or low proportions of aquatic organics relative to inorganic matter. In Korea, $KMnO_4$ consumption together with COD are commonly used to evaluate raw water organic concentration in water treatment plants. Figure 2 shows the removal efficiencies of turbidity and $KMnO_4$ consumption reduction under various COD/SS ratios ranging from 0.3 to 1.0. Here, the lower values of turbidity reduction and $KMnO_4$ consumption imply the higher removal efficiency. The turbidity reduction and $KMnO_4$ consumption also indicate the removal efficiencies of dissolved organic compounds and inorganic particles, respectively. Our results showed that the flotation efficiency was not more effective than sedimentation to remove turbidity (i.e., inorganic particles) when the COD/SS ratio was below 1.0 (i.e., high turbidity). The decrease of removal efficiency of DAF at low COD/SS ratios might have been caused by the presence of inorganic particles caused by runoff. Similarly, in the dry season the COD/SS ratio was over 1.0 that improved DAF efficiency by the tendency of algal-like particles to float. As shown in Fig. 2b, $KMnO_4$ consumption of DAF (i.e., organic removal efficiency) was greater than that of sedimentation in the whole range of COD/SS ratios. On the basis of the experimental results, the ratio of COD/SS is a good parameter to provide useful information on the performance of DAF and CGS processes.

As mentioned earlier, many studies have reported the effectiveness of the DAF process in treating algae-laden water. Although chlorophyll-a concentration is not an environmental criterion for lakes, it is regarded as an

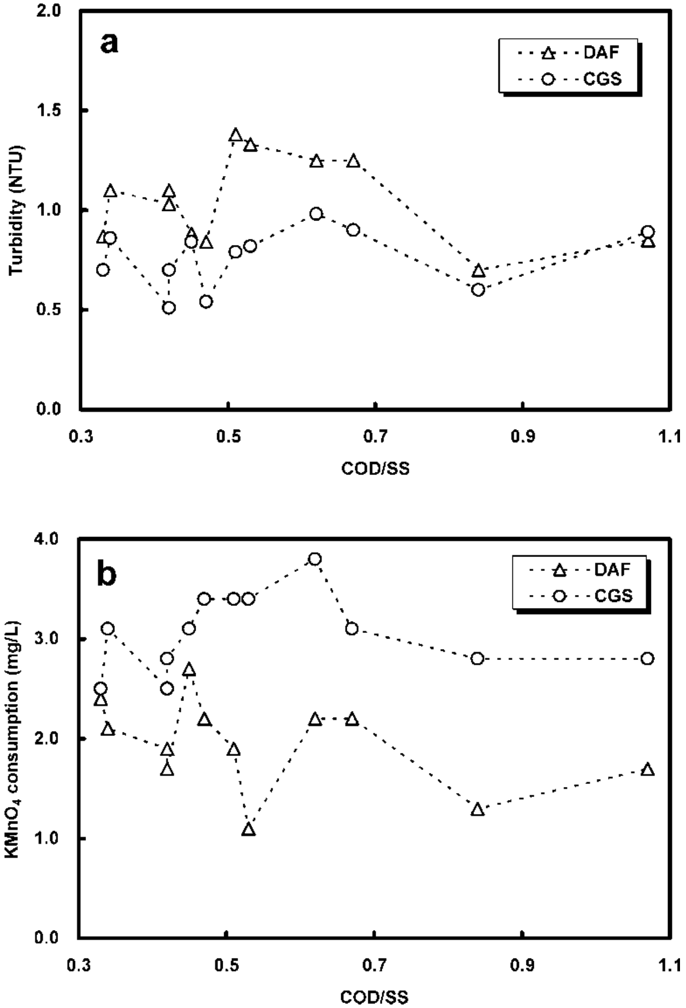

Figure 2. Variation of turbidity and $KMnO_4$ consumption in terms of the COD/SS ratio.

important parameter to indicate algae concentrations in Korea. Therefore, both the ratio of chlorophyll-a/SS and COD/SS should be taken into account in evaluating the feasibility of the DAF process. Figure 3 shows the removal efficiencies of turbidity reduction and $KMnO_4$ consumption under various chlorophyll-a/SS ratios ranging from 0.3 to 2.2. As expected, turbidity reduction (i.e., inorganic removal efficiency) by sedimentation exceeded that of DAF while $KMnO_4$ consumption (i.e., organic removal efficiency) of DAF was greater than that of sedimentation in the whole range of chlorophyll-a/SS ratios.

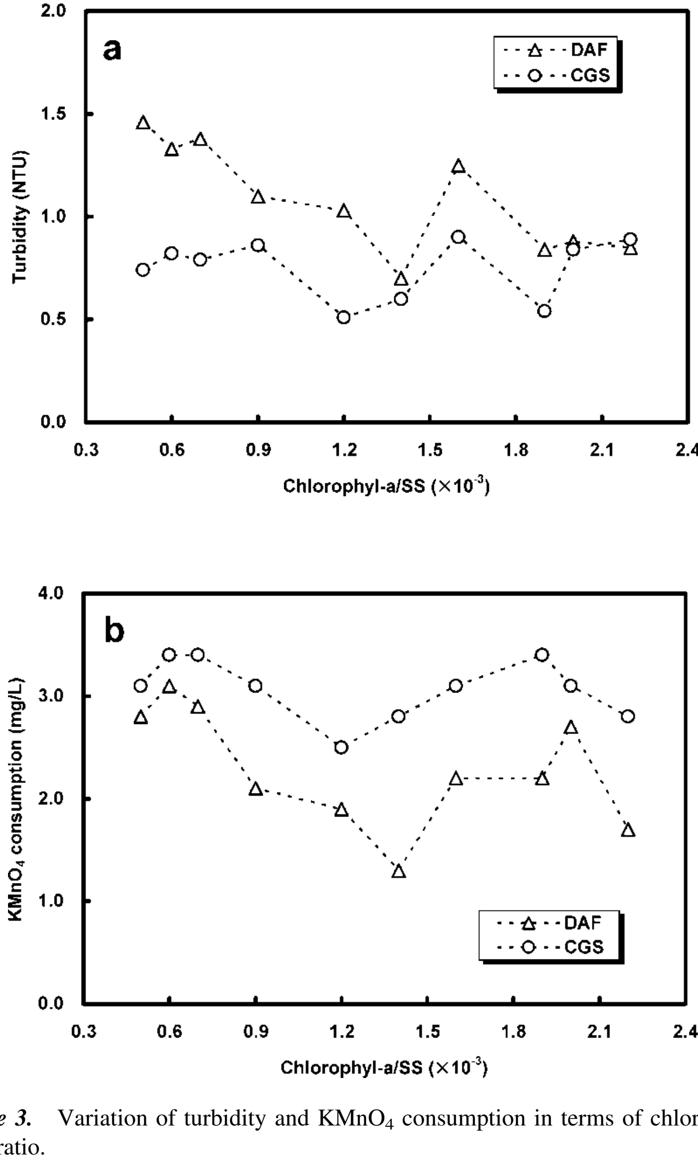

Figure 3. Variation of turbidity and $KMnO_4$ consumption in terms of chlorophyll-a/SS ratio.

Influence of Rainfall Intensity on Particle Separation

DAF is an effective water treatment process for algae-laden waters with low turbidity. However, it has limitations in dealing with high inorganic concentrations (i.e., high turbidity) and low alkalinity that result from runoff. Figure 4 shows the influence of rainfall (July in Korea) on turbidity and

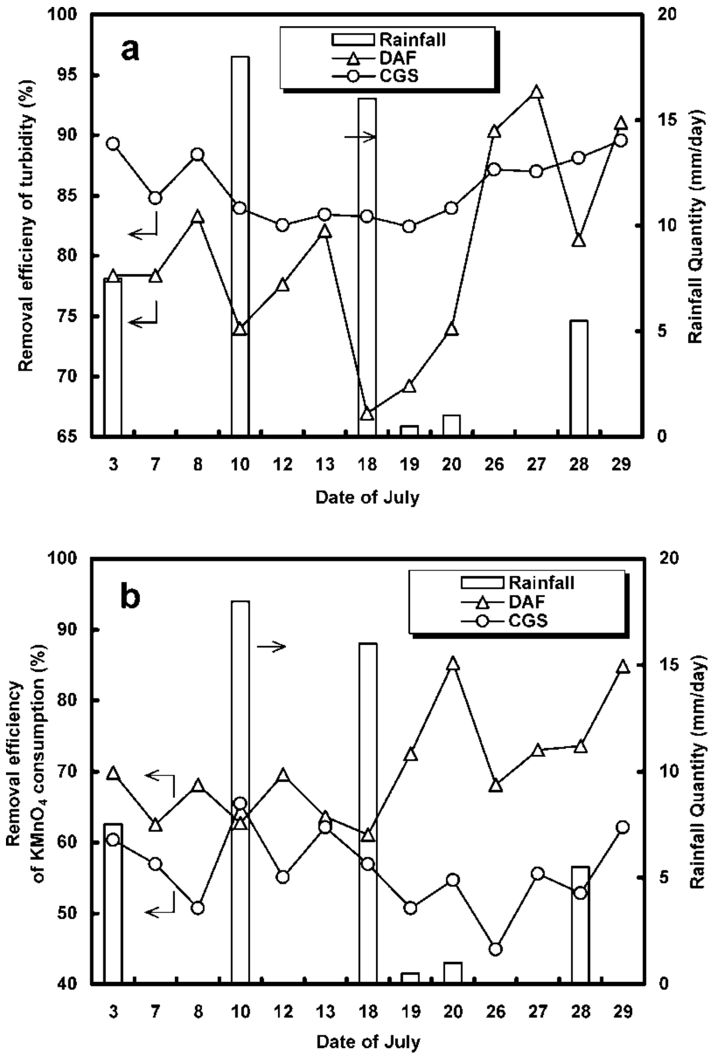

Figure 4. Influence of rainfall on turbidity and $KMnO_4$ consumption during the rainy season.

$KMnO_4$ consumption at the SJK water treatment plant (75,000 m^3/day, Korea). It was found that the turbidity removal efficiency by DAF was highly dependent on the rainfall intensity, while CGS efficiency was almost independent from rainfall intensity (Fig. 4a). This result implies that the DAF process was more sensitive to the presence of inorganic particles due to rainfall than the CGS process. However, the organic removal efficiency (i.e., $KMnO_4$ consumption) was not influenced by rainfall (Fig. 4b). Thus, when the DAF process is applied for particle separation, the concentration of inorganic particles is an important operational factor during the rainy season.

Distribution of Inorganic Particles in Raw Water

The DAF process involves both hydrodynamics and surface chemical interactions between particles and bubbles (9–15). In general, the role of surface charge for small particles (<10 μm) is more important than the hydrophobic nature of the particle. The forces of electrostatic interaction originating from the surface charges of the bubble and particle act beyond the effective range of the hydrophobic forces originating from the van der Waals forces. Also, the wetting perimeter of adhesion of the particles (<10 μm) on the bubble surface is very small, compared to that of large particles (>100 μm) (16). To investigate which range part of particles was easily floated by DAF, batchwise experiments were carried out using a vertical column (the diameter and height of the column are 15 cm and 180 cm, respectively). The results revealed that the sizes of particles removed with micro-bubbles were smaller than the residual particle sizes in flotation column. The Gaussian mean value of floating particle size was about 200 μm while that of residual particles was 298 μm (Fig. 5). The residual particles were not formed as

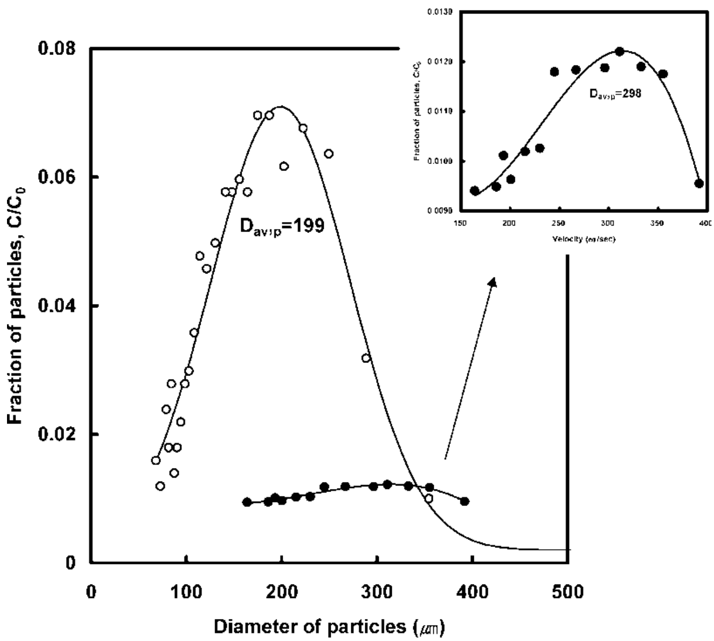

Figure 5. Distribution of inorganic flocs and settling flocs after flotation.

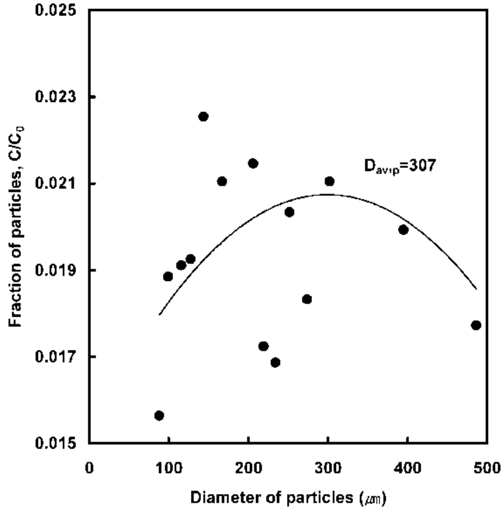

Figure 6. Size distribution of break-up particles detached with bubble from the water surface.

bubble-floc agglomerates. Even when particles were combined with microbubbles, some particles detached from the bubbles in the floated layer on the water surface. The mean value of detached particles (also called break-up particles) was approximately 307 μm (Fig. 6). From these results, we

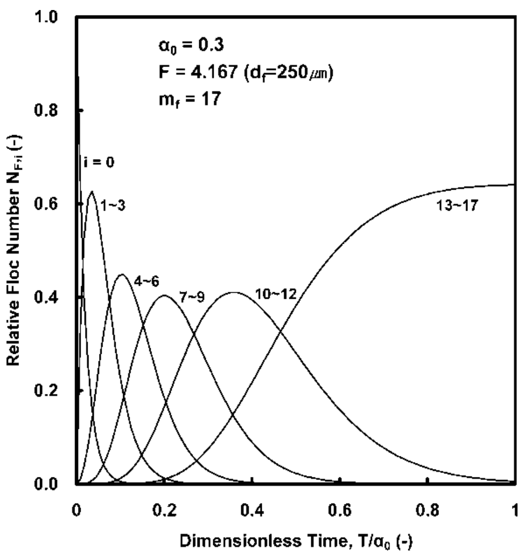

Figure 7. Simulated result of floc-bubble number with mixing time.

found that DAF was unfavorable to remove large (over 300 μm) inorganic particles because those particles either were not combined with bubbles, or detached from the floated sludge layer on the water surface. In this case, therefore, a primary settling process (i.e., a small settling tank) prior to the DAF process may be required to remove sand particles.

It is essential to examine the decrease of free air bubble concentration with time in a bubble-floc attachment process. Fig. 7 denotes an example of simulated results using Eqs (1)–(5) by employing the Euler method. Assuming the value of α_0 (0.35), the time variation of the number of flocs

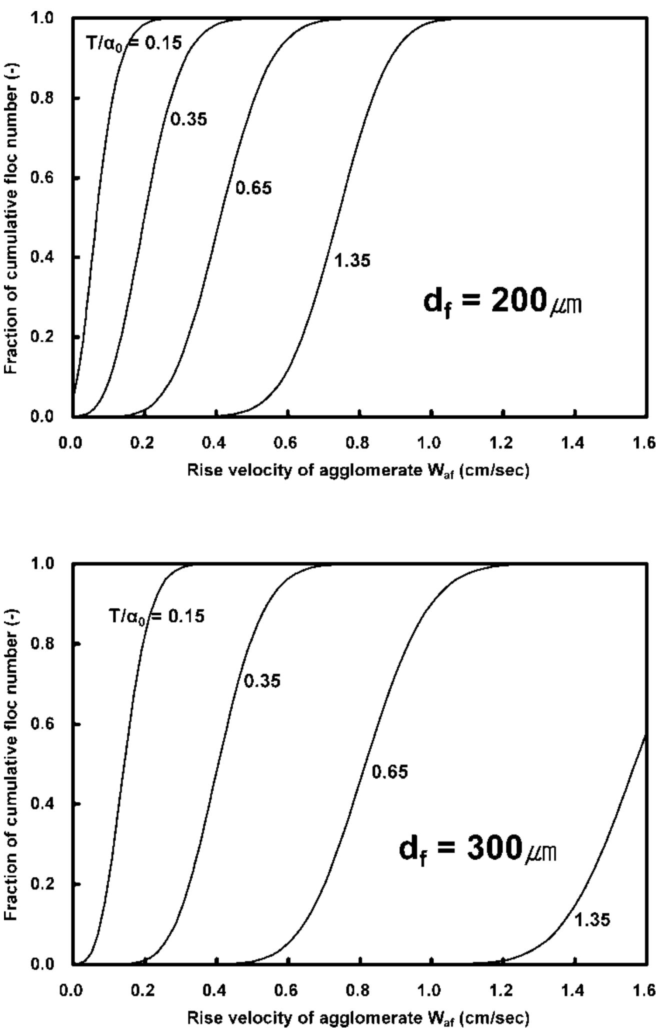

Figure 8. Simulated result of rise velocity distribution of agglomerate.

which attached i bubbles $N_{F,i}$ can be calculated for a given characteristic value or number of bubbles and flocs, and by mixing them. As expected, the relative floc number increased with the mixing time.

Rise Velocity of Floc-Bubble Agglomerate

Both the number of bubbles attached, and the floc size have a dominant effect on the rise velocity of bubble-floc agglomerates. It has been known that the number of attached bubbles, i, is usually in the range of 1 to 10, the effective density of the floc is 0.001 to 0.1 g/cm^3, and the relative diameter of the floc to bubble, d_f/d_a is 1 to 10 (3). The bubble attachment to flocs can be predicted by Eqs (6)–(9) under given conditions of flocs, bubbles, and mixing state. Figure 8 shows the simulated rise velocity distribution of floc-bubble agglomerates when the initial collision-attachment factor (α_0) is 0.35 with a varying floc size (200 and 300 μm). Other model parameters used in the simulation are listed in Table 4. As expected, the fraction of cumulative floc number increased with the rising velocity of agglomerate, W_{af}.

The initial collision-attachment factor (α_0) is considered as the most important factor in evaluating the DAF process. Thus, we examined the values of α_0 for inorganic particles by comparing the experimental data and the theoretical prediction. Figure 9 shows the results of the rise velocity distribution of agglomerate with different values of α_0 (0.20~0.45). As a result, a good fit between the experimental and simulated results is observed when initial collision-attachment factor (α_0) is about 0.30. Considering that the values of α_0 generally range from 0.3 to 0.4, the value implies that the collision-attachment efficiency of the inorganic particle is very low. Therefore, it appears that sedimentation prior to flotation is required for the removal both of larger inorganic flocs and algae-laden organic particles, considering highly turbid raw water characteristics due to heavy rainfalls in Korea.

Table 4. Model parameters used in simulation

Parameters	Unit	Value
Diameter of bubble (d_a)	μm	60
Initial free bubble number (N_a)	—	5×10^4
The effective mean energy dissipation rate (ε_0)	W/cm^3	6.0×10^{-3}
Density of water (ρ_w)	g/m^3	1.000
Density of air (ρ_a)	g/m^3	1.17×10^{-3}
Viscosity of water (μ)	$g/cm \cdot sec$	1.306×10^{-2}
Constants of the floc density function (a)	g/m^3	1.04×10^{-4}
Constants of the floc density function (K_p)	—	1.65

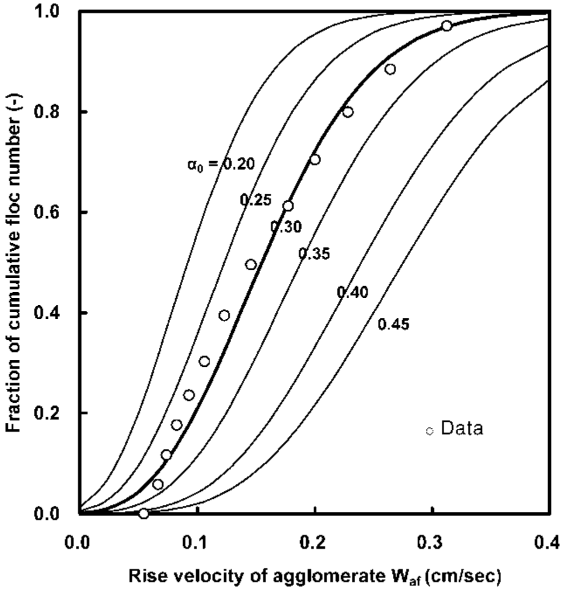

Figure 9. Estimation of the initial collision-attachment factor (α_o).

SUMMARY AND CONCLUSION

Experimental and theoretical studies on the effect of inorganic particles caused by turbid runoff were carried out under various COD/SS and chlorophyll-a/SS ratios. It was found that removal efficiency by DAF was lower than by CGS for low range of chlorophyll-a/SS ratios, attributable to the presence of dense inorganic particles. The initial collision-attachment factor (α_0) of the DAF process was calculated by a population balance model, giving a relatively low value of 0.3 for floc sizes ranging from 100 to 400 μm. When the inorganic particles were larger than about 300 μm, they were not easily removed by DAF because the particles were not combined with bubbles or detached from the floated sludge layer on the water surface. Thus, it seems that sedimentation prior to flotation is required for the effective separation of larger flocs, typically formed due to heavy rainfalls and highly turbid runoff in Korea.

NOMENCLATURE

d_a	Bubble size [μm]
d_f	Floc size [μm] Diameter of bubble-floc agglomerate [μm]
F	Floc size [−] ($=d_f/d_a$)
g	Gravity acceleration [m/s^2]

k	Constant of drag force [−]
K_p	Constants of the floc density function [−]
m_f	Maximum attachable number of bubbles on a F-size floc [−] ($=\alpha_0 F^2$)
$n_{f,i}$	Number of flocs with attached i bubbles [cm^{-3}]
n_a	Free bubble concentration
N_a	Free bubble concentration [−] ($=n_a/n_{a0}$)
N_0	Total floc concentration [−] ($=n_{f0}/n_{a0}$)
$N_{f,i}$	Concentration of f-size flocs
$N_{F,i}$	Concentration of F-size flocs with i bubbles [−] ($=n_{f,i}/n_f$)
P	Pressure [kPa]
r	Recycle ratio [−]
t	Time [sec]
T	Normalized mixing time [−] ($=(3/2)\pi\beta(\varepsilon_0/\mu)^{1/2} n_{a0}\, d_a^3\, \alpha_0\, t$)
W_{af}	Rise velocity [cm/sec]

Greek Letters

α	Collision-attachment factor [−]
β	Constant [−] ($=\sqrt{1/15}$)
ε	Effective energy dissipation rate [W/cm^3]
μ	Viscosity of water [$g/cm \cdot sec$]
ρ	Density [g/m^3]
θ	Mixing time [−]

Superscripts and Subscripts

a	Air bubble
af	Air flotation
0	Original or initial values
f	Floc
w	Water

Abbreviation

CGS	Conventional gravity sedimentation
COD	Chemical oxygen demand
DAF	Dissolved air flotation
SS	Suspended solids

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