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Abstract: This study attempted to investigate the relationship between the floc size and efficiency of a DAF (Dissolved Air Flotation) method using a PDA (Photometric Dispersion Analyzer), which is used to monitor floc generation via on-line access. This study applied actual measurements to investigate how the size of bubbles affected the flotation velocity, and introduced similar results to the theoretical flotation velocity reported in the literature. The results were found to play a role in improving the reliability in the evaluation of the flotation velocity of floc-bubble aggregates. From the results of the evaluation of the electrostatic characteristics for application to DAF treatments, the amount of coagulants was determined on the basis of the zeta potential value, which had to be controlled in the order of $+2 \sim +5$ mV to improve the treatment efficiency. The results of the rapid mixing intensity test using a PDA demonstrated that G value of 900 sec^{-1} for $1 \sim 3$ sec provided excellent treatment efficiencies in a DAF process. In addition, from the results of the flocculation test based on the flocculation index, the flocculation combination of 70/50 sec^{-1} gave reasonable results for DAF operation.

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Keywords: Bubble-floc aggregate and rising velocity, bubble size, dissolved air flotation (DAF), floc size

INTRODUCTION

Generally, DAF performs well with pinpoint flocs. The large settleable flocs necessary for conventional sedimentation are not required and should be avoided (Valski, 1997) (1). Consequently the flocculation mixing intensity used with DAF is higher than that for conventional gravity sedimentation. With respect to the relationship between the floc size and treatment efficiency of a DAF process, Edzwald (1995) reported that it is not necessary to generate flocs over a long-term period because the appropriate floc size can be configured as pin floc sizes ($10 \sim 30\,\mu m$) in a floc-generating area to obtain maximum efficiency (2). However, Fukushi (1998) argued that it is necessary to produce flocs over a long-term period because a large floc size, $10 \sim 100\,\mu m$, is effective in a DAF process (3). Also, Han (2002, 1999) reported that similar-sized particles and bubbles showed high level collision efficiencies (4,5). For instance, if small bubbles collide with small particles, then the collision efficiency, i.e., the chance of a permanent attachment between a bubble and floc, will be increased. In addition, he found increased treatment efficiencies with high collision efficiency factor values between small-sized particles and small-sized micro bubbles, and small-sized particles and large-sized micro bubbles.

Accordingly, in this study, the pretreatment conditions for an optimal DAF process operation were investigated by comparing and evaluating features during actual floc formation and the flotation velocity using different coagulant and flocculation mixing intensities to improve the flotation velocity and floc removal efficiency in a flotation process. For such analysis, the actual flotation velocity was measured using a PIA (Particle Image Analyzer), which photographs and analyzes the images of the floc-growth and the micro bubble and particle behaviors using a microscope and image analyzer. The size of bubbles and flocs were able to be measured and the conditions of floc formation for flotation evaluated with this device. This study attempted to investigate the relationship between the floc sizes and efficiency of a DAF method using a PDA (Photometric Dispersion Analyzer) developed by Gregory (2003) and Nelson, which was used to monitor the floc generation via on-line access (6).

METHODS

The testing water was produced using suspended mother liquor (Gorden, 1991) (7), which was made by taking 600 mL of the upper layer of the sediment solution prepared using Kaolin (Junsei Chemical) powder (dried at 105°C and 5 g of the powder was mixed with 150 mL of distilled water). The solution was mixed for 24 hours before filling with distilled water to 200 mL, and mixed at 6000 rpm for 3 min, with the final solution then made up to 1 L with distilled water and allowed to settle for 24 hours without stirring. In addition, the final solution was spiked with regular tap water (Alkalinity: 19 mg/L as $CaCO_3$, pH: 6.5). The coagulants used in this test were LAS (Liquid Aluminum Sulfate, Al_2O_3 8%), PAC (Poly Aluminum Chloride, Al_2O_3 11%) and PAHCs (Poly Aluminum Hydroxy Chloro Sulfate, Al_2O_3 17%) by diluting with distilled water to the specific concentration.

With respect to the measurement of the bubble size, the floc size, the sedimentation velocity, and the flotation velocity, a PIA (Particle Image Analyzer) was used to measure the floc growth rate by sequentially capturing the floc images in water. The equipment was composed of a Microscope (SZ61TRC, Olympus, Japan), High Speed CCD Camera and Image Analyzer (Image-Pro Plus ver. 5.0), as shown in Fig. 1. A flotation cell was vertically placed on the upper part of a Jar tester of the PIA, to enable both static and moving images to be photographed through the microscope and high-speed camera after the fixing of underwater particles in the flotation cell. The image analyzer can measure velocity vectors and the size of particles from the photographic images using a tracking technique.

A PDA (Photometric Dispersion Analyzer, PDA 2000, Rank Brothers Ltd, UK) was also used to analyze the indirect evaluation of floc

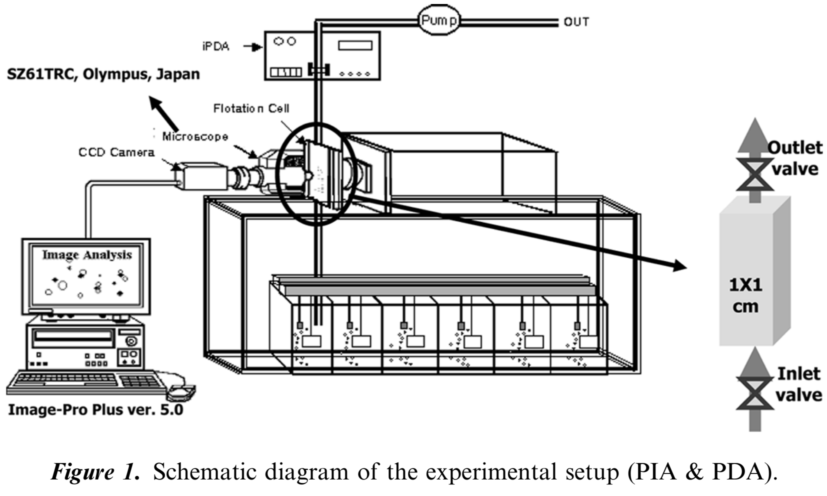

Figure 1. Schematic diagram of the experimental setup (PIA & PDA).

sizes and growth rates. Floc sizes were calculated by substituting the values measured using the PDA into the equation proposed by Tambo (1979) (8). The PDA can be used to monitor the characteristics of flocs generated by flocculation via on-line access, and was connected to a DAF Jar Tester (Model: DBT6, EC Engineering Co, Canada). This system can be applied to a flotation test on a Bench scale, by connecting dissolved air lines to a Jar Tester. The type of Jar used in this test was 198(H) $\times$ 80(W) $\times$ 80(L) mm in size, with a volume of 1 L. A 40 $\times$ 60 mm PBT type impeller and an 8 L saturator were used in the test. The treatment efficiency was measured after 3 min of flotation using a turbidimeter (Model: 2100 N Turbidimeter, Hach). In addition, a 3 mm exclusive tube of PDA was connected, with a flow rate of 20 mL/min as measured using a metering pump. The measured values included Direct Current (DC), Root Mean Square (RMS), as well as their Ratio (RMS/DC), referred to as the Flocculation Index (FI). The FI is an indirect indicator representing the growth of particles. The smaller the particles, the smaller the value, and as the size of a particle becomes larger, the value increases (Gregory, 2003) (6). These measured values are designed to be converted into a digital signal type at PDA device and, for continuous analysis, stored in the computer.

EXPERIMENT RESULTS

Analysis of Bubble Sizes and Flotation Velocities

The size of the bubbles in a DAF process can be greatly influenced by the pressure difference before and after the nozzle as well as by the shape of the nozzle (AWWA, 1999) (10). In general, the size of bubbles approximately ranged from 10 to 100 μm (average: 40 μm) under applied pressures of 4 to 6 atm (Edzwald, 1995) (2). The pressure significantly affected the bubble sizes. That is, the bubble sizes decreased with increasing applied pressure. However, Schers and Van Dijk (1992) reported that there is a critical pressure where no additional decrease in the bubble size occurs under a specific pressure, which was proposed as 5 atm (9).

The bubble size in a DAF process is an important factor in the flotation velocity (AWWA, 1999) (10). Thus, a PIA method was applied to measure the influence of the bubble size on the flotation velocity. The applied pressure to generate bubbles ranged from 4 to 5 atm, with an interval of 0.5 atm. Also, the bubble sizes were measured at three different pressures. The flotation velocity of bubbles was measured by tracking the bubbles generated under each condition. This tracking method allows

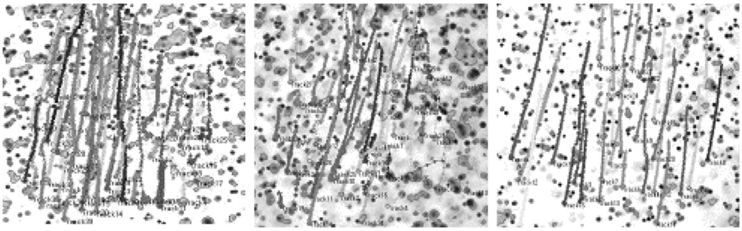

Figure 2. The results of image analysis for bubble rising velocity by tracking bubbles using PIA.

objects to be followed in sequential images, and automatically measures the distance traveled and calculates the moving velocity (Fig. 2). The results of the analyses of this test proved to be similar to the theoretical flotation velocity of bubbles, as illustrated in Fig. 3. However, the measured flotation velocities appeared to be slightly lower than those obtained theoretically, because those measured could be affected by the experimental conditions, which were different from ideal conditions, such as the shear force of the wall of the tube and the Reynolds number, etc. A test to improve the flotation velocity of floc-bubble aggregates was also conducted based on these results.

On the basis of above results, the theoretical flotation velocity was calculated by applying the diameter (an average 40 μm) of the flocs and micro bubbles, as measured by PIA, to the equation proposed by Schers

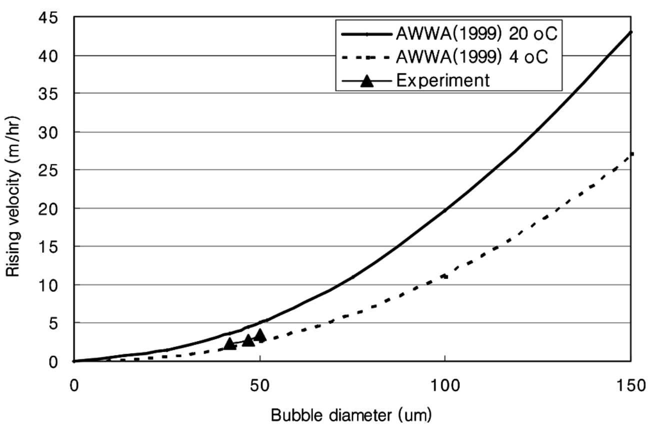

Figure 3. Comparison of rising velocities between experimental values (20°C) and theoretical ones (20°C, 4°C) (AWWA, 1999) (10).

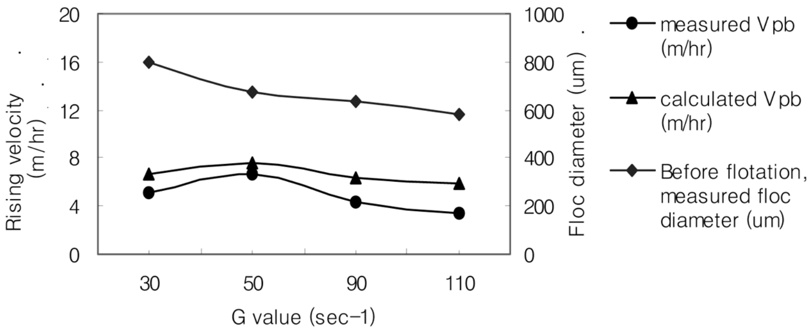

Figure 4. Comparison of rising velocities of floc-bubble aggregate between the theoretical values and the measured ones.

and Dijk (1992) (9).

$$v_{pb} = \frac{g(\rho_w - \rho_{pb})d_{pb}^3}{18\mu} \qquad (1)$$

$$\rho_{pb} = \left[\frac{\rho_p d_p^3 + N_{ab}\rho_p d_p^3}{d_p^3 + N_{ab}d_p^3}\right]$$

$$d_{pb} = \left[d_p^3 + N_{ab}d_p^3\right]^{1/3}$$

v_{pb}: The rising velocity of the floc-bubble aggregate (m/hr);
ρ_{pb}: The floc-bubble aggregate density (kg/m^3);
N_{pb}: The number of air bubbles attached to a floc.

The flotation velocity was measured by tracking a floc using PIA, and compared with the theoretically calculated values. In a comparison, these two velocities showed very similar values, as shown in Fig. 4. With a flocculation mixing intensity of 50 sec^{-1}, the measured velocity was 6.71 m/hr, the fastest, and the treatment efficiency at that velocity was the highest. Accordingly, it was expected that theoretically the flotation velocity would be fast, since the density of the floc was low while the size was large under a low flocculation mixing intensity (Velocity Gradient (G value): 30 sec^{-1}), but the experimental results revealed that the flotation velocity was unexpectedly low. This was attributed to the possibility of floc disintegration due to the low density of the floc.

Optimal Zeta Potential for Improving Treatment Efficiencies in a DAF Process

It is known that a flocculation process of a DAF system can be greatly influenced by certain matrix chemical characteristics, such as pH, alkalinity, types of coagulant, and the condition of physical flocculation (Edzwald, 1995; Han, 2002; Kwon, 2004) (2,4,13). Han et al. (2001) reported that one of the most important factors determining the DAF treatment efficiency was the electrostatic characteristics, such as the zeta potential. The size of particles also significantly affects the efficiency (11). The goal of pretreatment in a DAF process is to determine the mixing time required to create the appropriate floc sizes to obtain maximum treatment efficiencies and discover the specific combination between flocs and micro bubbles to generate attachment. Thus, in this study, the zeta potential was measured after coagulation, with the relationship between the zeta potential and treatment efficiencies analyzed (raw water quality: Turbidity ($1 \sim 5$ NTU), Alkalinity ($25 \sim 30$ mg/L as $CaCO_3$), pH ($6 \sim 7$) and Zeta potential ($-13 \sim -19$ mV)).

This study also compared the results of the changes in zeta potentials and turbidity of treated water under various conditions, i.e. the types and amounts of coagulants (PAC, PAHCs, and LAS) in a flotation process. The raw water was sampled from the Songjeon water treatment plant, located in Gangwon province, Korea. Figure 5 illustrates the results of the comparison. The optimum dose range varied with the species of the coagulant; the range for PAHCs was broadest, followed by PAC, and then LAS. The highest turbidity removal efficiency for the DAF

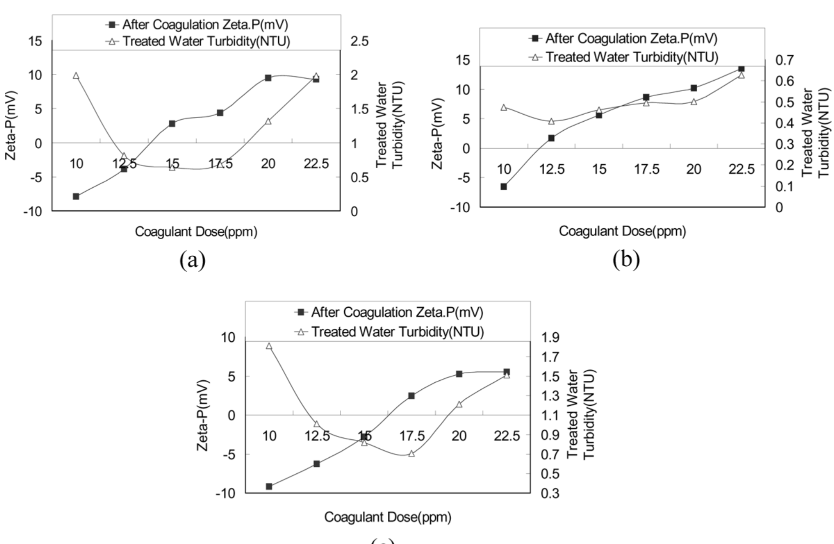

Figure 5. The change of zeta potential and turbidity with the dose of coagulant ((a) PAC, (b) PAHCs, (c) LAS).

treatment was found in the zeta potential range of $+2 \sim +5\,\text{mV}$, regardless of the type of coagulants used. The residual turbidities were within the range 0.4 to 0.7 NTU, depending on the coagulant. Thus, the amount of coagulants required to improve treatment efficiencies has to be determined considering the optimal zeta potential within the range from +2 to $+5\,\text{mV}$, which is also the actual electrostatic characteristic range of real DAF systems.

In order to evaluate the change of floc size during flocculation, the sequential floc images were captured with time (Fig. 6). These showed that the floc size increased with increasing flocculation time, but grew

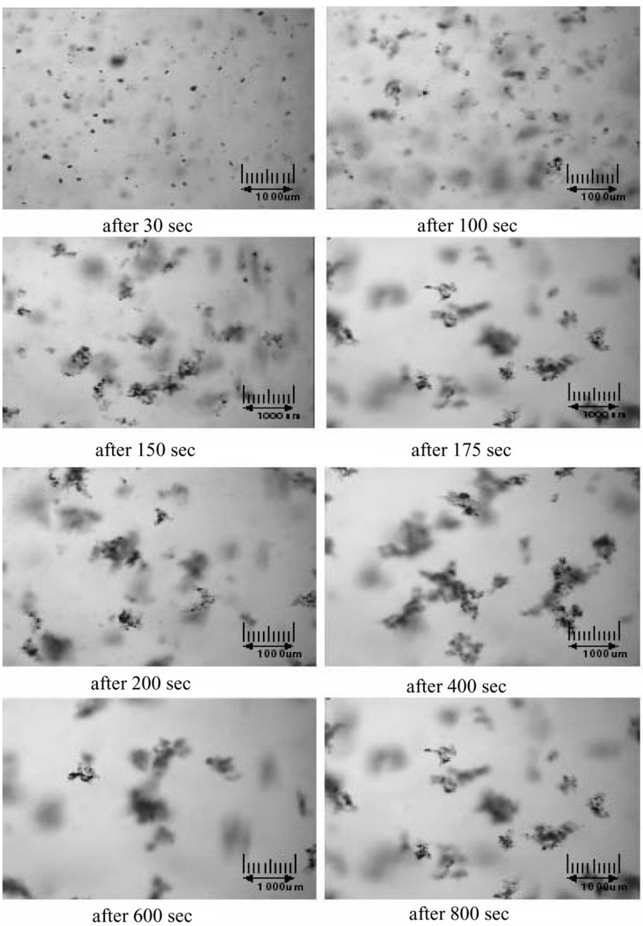

Figure 6. Photographs of floc formation at elapsed times of flocculation process.

no larger after a given time period. This result was similar to the floc size evaluation using a PDA.

Evaluation of the Size of Flocs Using a PDA

The evaluation of the floc size in an artificial water was performed to discover the optimal conditions for a flotation process using a PDA. Two different coagulants (LAS and PAC) were applied to the raw water in which the coagulant application ratio representing the minimum turbidity was compared for each case. From the results of this comparison, the optimum dose to obtain the minimum turbidity was found to be 10 ppm of LAS and 8 ppm of PAC. Figure 7 illustrates the results of the PDA tests for LAS and PAC. LAS demonstrated a slightly higher flocculation level than PAC. These two coagulants were applied to the artificially prepared water at 10 NTU. To verify the variation in the appropriate coagulation conditions due to a rapid mixing intensity, a Jar test was performed using raw water from the Hoeng Seong Dam. The raw water had a turbidity of 1.35 NTU. The results of the PDA test showed the highest treatment efficiency at G value of 900 sec^{-1} for 1∼3 sec, as previously proposed by Kawamura (1996) (12). The results

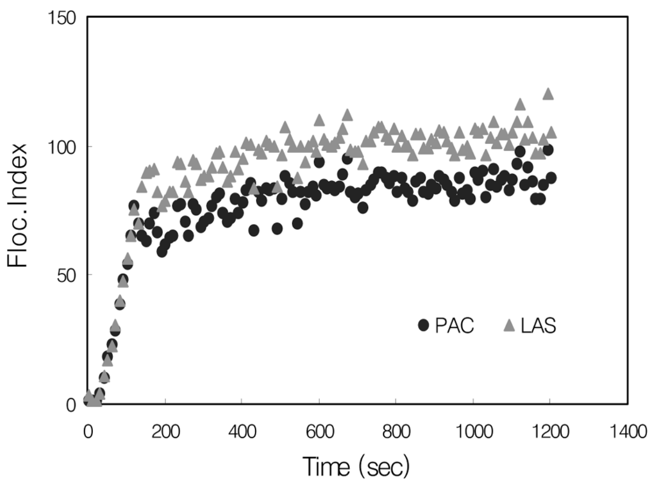

Figure 7. Comparison of flocculation index of PAC and LAS (Rapid mixing intensity (G value): 900 sec^{-1} for 3 sec, combination of flocculation mixing intensity (G value): 70/50 sec^{-1} for each 10 min).

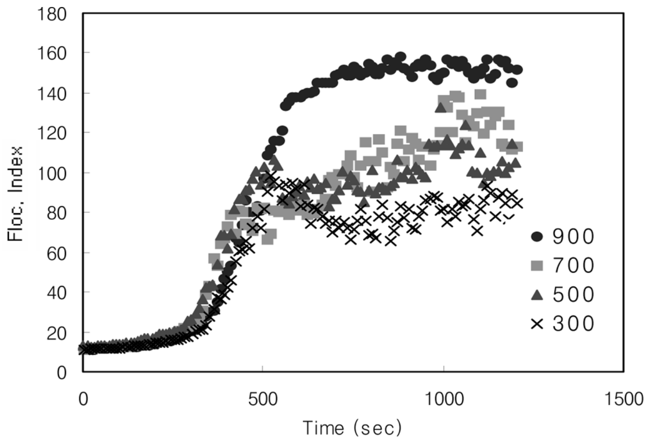

Figure 8. Comparison of Flocculation Index at four rapid mixing intensities with 3 sec of hydraulic retention time (Rapid mixing intensity (G value): 900, 700, 500, and 300 sec^{-1}, combination of flocculation mixing intensity (G value): 70/50 sec^{-1} for each 10 min).

also showed a high level of distribution in the flocculation index at G value of 900 sec^{-1} (Fig. 8).

The results of the jar test to investigate the appropriate combination of G values in a flocculation basin showed a high turbidity removal efficiency of 94% using LAS with a G value combination of 70/50 sec^{-1} (primary basin/secondary basin). Also, the PDA test with a rapid mixing intensity of 900 sec^{-1} on the application of 15 ppm LAS in the artificially prepared water with a turbidity of 10 NTU demonstrated high flocculation indices with the G value combinations of 70/50 sec^{-1} and 90/70 sec^{-1}. However, 70/50 sec^{-1} showed a slightly higher flocculation index (Fig. 9). From the results of the PDA test under several turbidity conditions, 900 sec^{-1} of rapid mixing intensity, 70/50 sec^{-1} combination of flocculation mixing intensity and 15 ppm LAS in the artificially prepared water with turbidities of 5, 10, and 20 NTU, respectively, the case with 20 NTU showed the highest distribution of flocculation indices, as illustrated in Fig. 10. In the tests under the 3 different turbidity conditions, with a dose of 10 ppm LAS, a rapid mixing intensity configured at 900 sec^{-1} and the flocculation basin divided into two basins of 70/50 sec^{-1} G values, respectively, with a 10 min of hydraulic retention time each, the result showed that the flocculation index increased following the growth of flocs, where the value maintained a constant level after 400 sec of flocculation. In addition, the turbidity treatment efficiency according to the flocculation indices showed the highest efficiency when

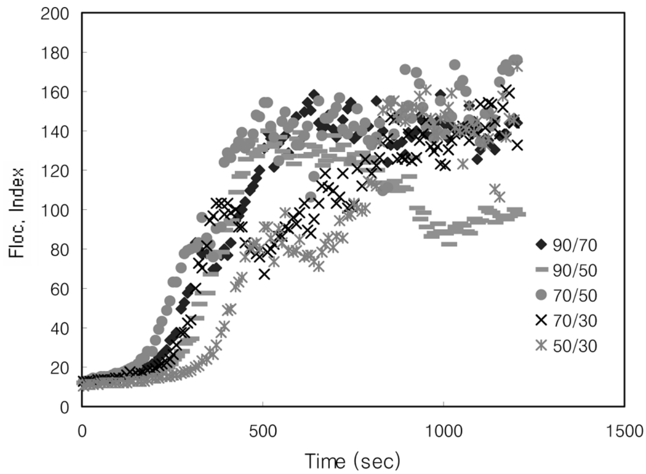

Figure 9. Comparison of Flocculation Index at five flocculation intensity conditions (Combination of flocculation mixing intensity (G value): 90/70, 90/50, 70/50, 70/30, and 50/30 sec^{-1}, Flocculation mixing time: 10 min for each step, Rapid mixing intensity (G value): 900 sec^{-1} for 3 sec).

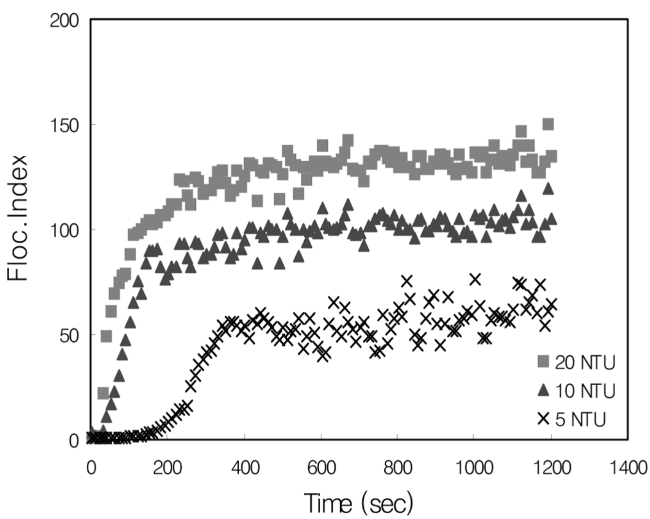

Figure 10. Comparison of Flocculation Index at different turbidities of the raw water (Turbidity of the raw water: 5, 10 and 20 NTU, Rapid mixing intensity (G value): 900 sec^{-1} for 3 sec, Combination of flocculation mixing intensity (G value): 70/50 sec^{-1} for each 10 min).

the turbidity of the treated water remained below 0.31NTU. Also, the flocculation index slowly increased in the raw water with a low turbidity.

CONCLUSIONS

This study applied the actual measurement of various parameters related to the flotation velocity of flocs and bubbles to investigate how the bubble size affects the flotation velocity. The measured flotation velocities showed similar values to those obtained theoretically in AWWA (1999) (10) and Schers and Van Dijk (1992) (9). It was evident that the results played a role in the improved reliabilities for the evaluation of the flotation velocity due to floc-bubble aggregates.

From the results of the evaluation of the electrostatic characteristics for applying DAF treatments, the amount of coagulants can be determined based on the zeta potential that will be maintained at $+2 \sim +5\,\text{mV}$ to improve the treatment efficiency.

From the comparative results of the impact of the treated water turbidity due to the flocculation mixing intensity in flotation process, it was found that the flocculation mixing intensity had a direct effect on the flotation efficiency. Therefore, its optimization is very important for improving the water quality of a water treatment plant.

From the results of the rapid mixing intensity test using a PDA, the condition of $900\,\text{sec}^{-1}$ for $1 \sim 3\,\text{sec}$ demonstrated excellent treatment efficiencies in the DAF process tested. Also, from the results of the flocculation test for the flocculation index, the condition of the flocculation combination of $70/50\,\text{sec}^{-1}$ gave reasonable results for DAF operation.

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