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A Case Study of the DAF-based Drinking Water Treatment Plant in Korea

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Abstract: Since 2003, a full-scale dissolved air flotation (DAF) process has been operated by the Korea Water Resources Corporation (K-Water) in the Songjeon drinking water treatment plant (SWTP). The SWPT was designed with an adaptable operation mode so that it is able to produce safe and stable drinking water, even when the raw water is in very poor condition. The adaptable operation mode is able to buffer the dramatic change in the characteristics of the raw water. During the service period of 2003 to 2006, the SWTP has shown a constantly sound performance for the treatment of high turbid water (64–430 NTU), yielding a significantly low level of turbidity (DAF treated water, 0.15 ~ 1.16 NTU; anthracite filtered water, 0.02–0.09 NTU). In terms of the DAF process, this work focused on suggesting some practical solutions that would cope with several difficult problems that occurred in the DAF-based drinking water treatment plant. These problems included the unexpected high turbidity occurring during the heavy rainfall season, the scraper problem due to the shortage of feed water to the DAF process, and the increase of turbidity due to the use of powder activated carbon (PAC) prior to the DAF process. In addition, from a cost-effective

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perspective, the relationship between the recycle ratio and the operating cost was investigated in the DAF process under two different recycle ratio conditions.

Keywords: Dissolved air flotation, drinking water treatment, high turbid water, variable weir

INTRODUCTION

The Songjeon drinking water treatment plant (SWTP), which has a total capacity of 200,000 m^3/day, was constructed in 2003. Since its construction, the SWPT has been operated by the Korea Water Resources Corporation (K water). The source water of the SWPT is from the Hweng-Sung (HS) Lake, which is a reservoir formed from dam construction. One of the main features of the SWTP is that a dissolved air flotation (DAF) process was initially integrated with several conventional processes (pre-chlorination, coagulation, sedimentation, and filtration). The main purpose of the DAF process in the SWTP was the treatment of algal-rich water, which is one of the major problems in Korean drinking water treatment plants that use dam source water. Many dams have been constructed in Korea by utilizing the terrain of the land in order to store water resources (1). There have been a number of reports that have revealed that dam source waters contain many algae species that have densities close to that of water (1,2). Edzwald, J. K. and Walsh, J. P. (1993, 1992) have suggested that algae-rich waters pose problems to conventional sedimentation, due to the tendency of algae to float on top of the water mass, due to its small size, its low cell density, and a negative surface charge (3,4). An alternative technique for the clarification of algal-rich waters is to use the DAF process (3,5,6). Janssens et al. (1993) proposed a section scheme for adequate treatment on the basis of the algae concentration and turbidity present in the raw water (7).

Using the results from bench-scale experiments, Bourgeois et al. (2004) demonstrated that DAF is more suitable for the clarification of lower density solids, while sedimentation proved to be more adaptable for treating waste residual streams that have higher density solids (6). Teixeira and Rosa (2006) investigated the efficiency of DAF to remove *M. aeruginosa* and compared this efficiency to that of the process of sedimentation. Their results showed that DAF is the best process to remove single cells of *M. aeruginosa*, yielding a very high removal of chlorophyll (93–98%) (8,9). Teixeira and Rosa (2006) also tried to integrate the DAF process with a nanofiltration (NF) membrane, reporting that the DAF-NF process is a safe barrier against *M. aeruginosa* and microcystins in drinking water.

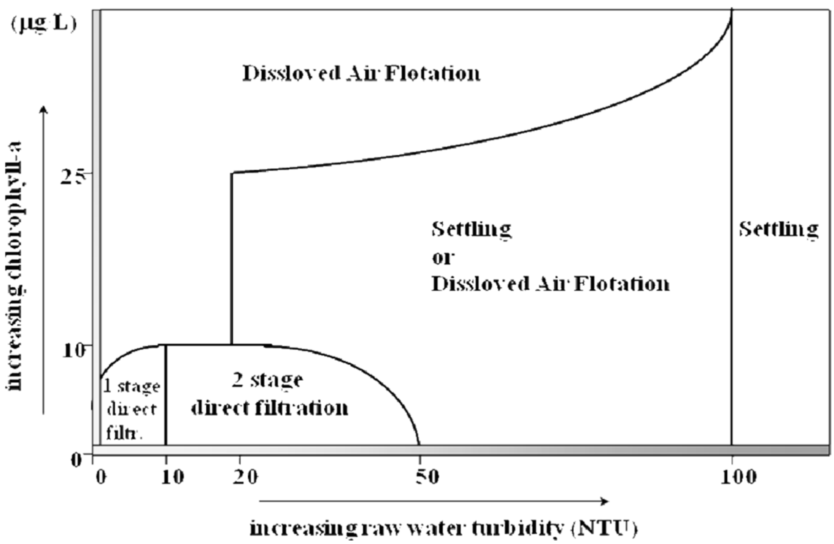


Figure 1. Selection diagram for algae and turbidity removal (10).

Another innovative feature of the SWTP is that its operation mode can be regulated according to the characteristics of raw water so that the effluent quality can be optimized and the operation costs can be reduced. The incorporation of new fundamental knowledge into the construction of modern treatment plants facilitates more compact designs and higher rates of operation. The limitations of each of the available unit operations make it desirable to combine and optimize the operation in an integrated way (10). Due to the limitation of the conventional process for the control of the variable conditions of water quality, adaptable operation modes (direct-filtration, pre-sedimentation/filtration, DAF/filtration, pre-sedimentation/DAF/filtration) in accordance with the raw water quality were adopted for drinking water production in the SWTP (3). Under the normal raw water condition (turbidity <10 NTU), the SWTP was operated by the direct-filtration mode. When the raw water contains high turbidity or algae blooms, powdered activated carbons (PAC) need to be injected prior to the coagulation process. When this is the case, the direct-filtration mode is not acceptable for operating the SWTP, and the other operation modes, as outlined above, using the DAF process, are selected for treatment sustainability.

During the service period of the DAF-based SWTP, attempts were made to solve several difficult situations that had been observed. These included an unexpected high turbidity during the heavy rainfall season, a scraper problem due to shortage of feed water to the DAF process, and an increase of turbidity due to the use of powder activated carbon (PAC) prior to the DAF process. The main purpose of this study is to suggest several practical methods to solve these serious problems that have occurred in the DAF-based drinking water treatment plant.

METHODS

Operating Conditions of the SWTP

The overall layout of the SWTP is illustrated in Fig. 2(a). The operation of the SWTP consists of five different processes, those of pre-chlorination, pre-coagulation/sedimentation, flocculation-DAF, high rate filtration, and post-chlorination. In order to optimize the coagulation efficiency, the SWTP has two pump diffusion units consisting of a duplex strainer, a mixing pump, a jet spray nozzle, a target plate, and chemical diffusers. The jet spray nozzle equipped in the raw water pipeline provides high intensity mixing by discharging between 3 and 5% of the total plant flow through the flash mix against the target plant, resulting in a uniform and rapid distribution of the coagulants into the raw water stream. Four types of operating modes strategically control these processes, as shown in Fig. 2 (b). These operating modes are

1) FULL PROCESS
2) DAF PROCESS
3) IN-LINE FILTRATION
4) DIRECT FILTRATION

Among the various operating modes, the DIRECT FILTRATION and IN-LINE FILTRATION modes are only used at the low (<5NTU) and common level (<3NTU) of turbidity in raw water. In cases of high turbidity and algae blooms, the SWTP is operated with the two operating modes of FULL PROCESS (>35NTU) and the DAF PROCESS (>5NTU) combined with the DAF plant. During the service period of 2003 to 2006, the SWTP was operated with only two operating modes (FULL PROCESS and DAF PROCESS) to test the performance of the DAF plant, regardless of the raw water quality. The service period of the FULL PROCESS operating mode is Jul.15 ~ Sep.1 and Sep.24 ~ Oct.4 in 2004, Jun.27 ~ Aug.1 in 2005, and Jul.13 ~ Oct.4 in 2006. With the exception of the service time of the FULL PROCESS, the SWTP was operated with the DAF PROCESS operating mode. Table 1

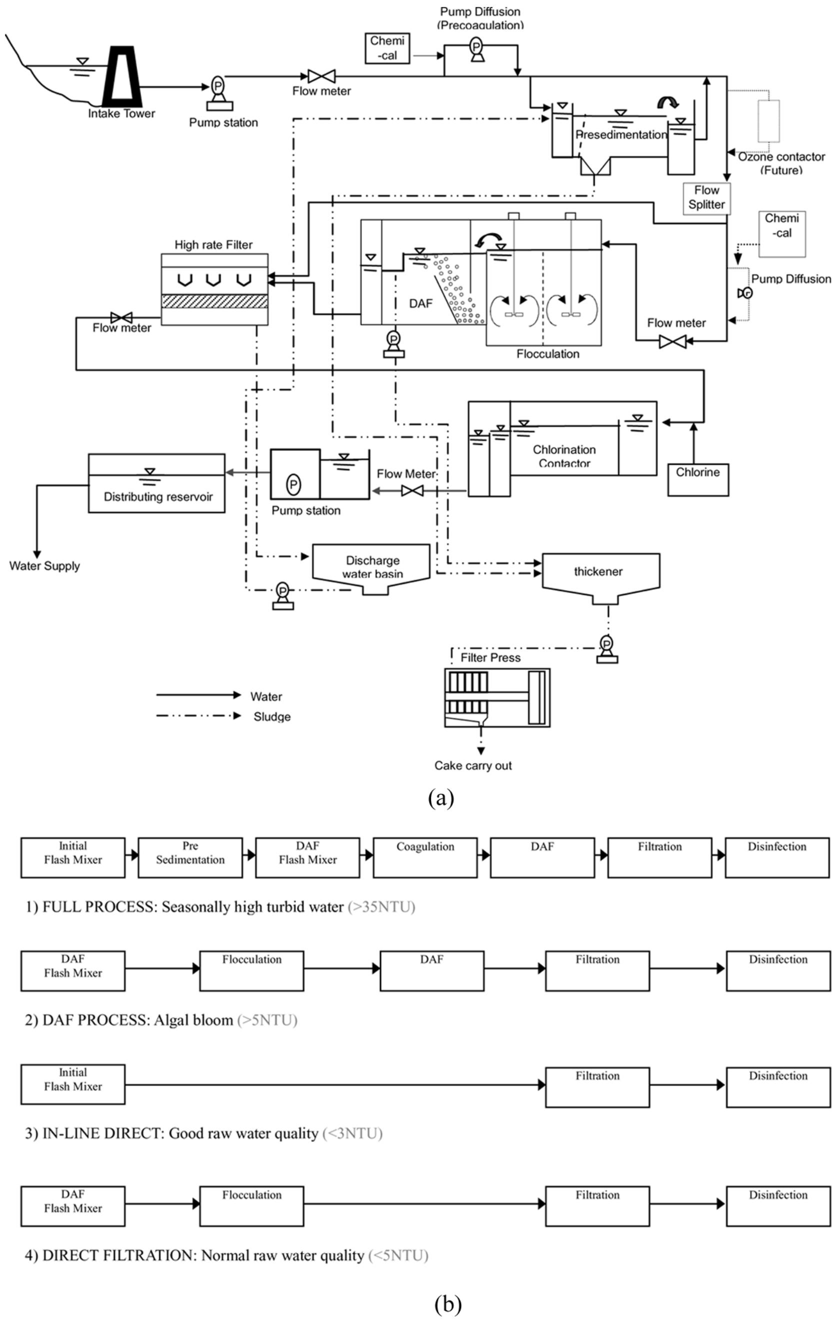


Figure 2. (a) Schematic diagram and (b) Various operating modes of the SWTP.

Table 1. Information on each process in the SWTP

Process	Parameter	Value
SWTP	Total plant capacity	200,000 m^1/d
Initial Flash mixer	Type	pump diffusion mixer
	G.t	1,000 ~ 1,600
Pre-sedimentation	Detention Time (h)	1
DAF Flash mixer	Type	Pump diffusion mixer
	G.t	1,042 ~ 1,699
Flocculation-DAF basin	Type	hydrofoil
DAF Flotation basin	Flow Rate (m^1/h)	1,042
	Loading (m/h)	11.9
	Detention Time (h)	0.21
Filters	Loading (m/d)	280
	Filter media	Anthracite1750 mm and 250 mm
	Type	Deep bed gravity (constant filtration speed)
Clear well	Detention Time (h)	3.53

summarizes the information on the design and operating parameters of each process installed in the SWTP. The SWTP has two identical full-scale plants, each one with a capacity of 100,000 m^3/d (total plant capacity = 200,000 m^3/d).

Raw Water Characteristics

The Hweng-Sung (HS) Lake was used as a drinking water source in the SWTP. Table 2 summarizes the average values of several parameters of water quality. The measurement was performed with two water samples from the HS Lake during 2001–2006 and influent water in the SWTP during 2004–2006.

RESULTS AND DISCUSSION

Case Studies under Several Problematic Conditions

Evaluation of the SWTP During the Heavy Rainfall Season

This study observed the concentrations of turbidity in raw water and treated water during several processes (such as pre-sedimentation,

Table 2. Raw water characteristics of the HS Lake and influent water in the SWTP

Raw water	Water characteristics						
HSL	COD (mg/L)	BOD (mg/L)	T-N (mg/L)	T-P (mg/L)	SS (mg/L)	Algae (Cell/mL)	Chl-a (mg/m^3)
Ave.	2.2	1.0	1.7	0.028	2.7	2455	3.6
Max.	2.4	1.1	2.0	0.050	4.6	4430	5.0
Min.	2.0	0.9	1.5	0.017	1.7	331	2.7
Influent water	pH	Alkalinity (mg/L as $CaCO_3$)	Hardness (mg/L)	Manganese (mg/L)	Chloride (mg/L)	$KMnO_4$ Consumption (mg/L)	
Ave.	7.1	21.6	28.0	0.03	2.1	4.3	
Max.	8.5	30.0	35.0	0.46	5.0	19.1	
Min.	6.2	8.0	15.0	0.0	1.0	2.2	

[a]Daily measurement during 2004.01.01 ~ 2006.12.31: pH, Alkalinity.
[b]Weekly measurement during 2004.01.09 ~ 2006.12.31: Hardness, Manganese, Chloride, $KMnO_4$ consumption.
[c]Monthly measurement during 2001.01 ~ 2006.12: COD, BOD, T-N, T-P, SS, Algae, Chl-a.
[d]All the samples were measured in duplicate.

anthracite-filtration, and DAF) in the SWTP. These were monitored while the SWTP was operating under the FULL PROCESS mode, by using both potable- and online turbidity meters (AN 2100, HACH and TB450G, Yokogawa) for the period between 2004–2006, as shown in Fig. 3(a). The average turbidity concentration in raw water was as low as 6.1 NTU. However, a significantly high level of turbidity (64–430

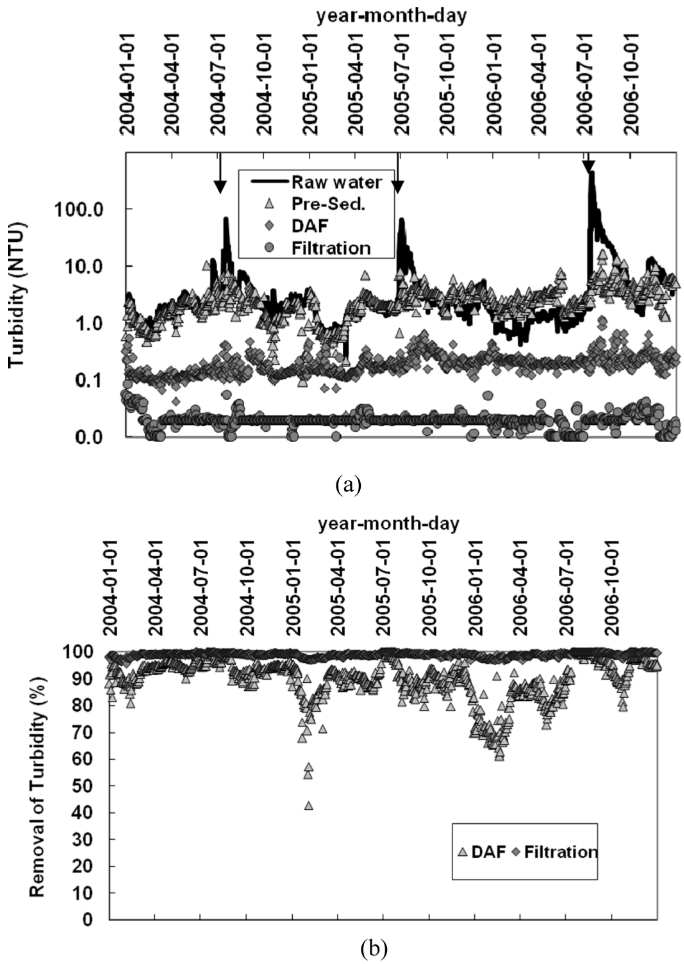


Figure 3. (a) Trends of turbidity in raw water and treated water by each process in the SWTP. (b) Removal efficiencies of turbidity by the DAF and Filtration processes. Arrow symbol = rainfall season, and the period of turbidity shown in this figure = 2004.1.1 ~ 2006.12.31.

NTU) was observed every heavy rainfall season (rainfall > 300 mm). Even though the turbidity dramatically increased, the water that was treated by the processes of DAF and anthracite-filtration revealed a low and stable concentration of turbidity, yielding 0.15–1.16 and 0.02–0.09 NTU, respectively. Figure 3(b) shows the efficiencies of the removal of turbidity by these two processes (DAF and Filtration). Even though the treated water in the DAF process showed unstable removal efficiency in some periods, it was found that the DAF process had a sound treatment capacity for removing the turbidity. The anthracite-filtration process also showed a high performance, maintaining a >95% efficiency in the removal of turbidity. It should be noted that the role of pre-sedimentation was important for the DAF process to maintain its performance of turbidity removal. Actually, the removal of turbidity by the pre-sedimentation process was almost negligible. However, during the heavy rainfall season, the pre-sedimentation process reduced the turbidity in raw water up to less than 10 NTU. This indicates that the turbidity increased by the heavy rainfall could be mainly composed of clay and weighty particles, which are easily and rapidly removed in the sedimentation basin. Since these types of particles could damage the DAF process, the FULL PROCESS operating mode, including the pre-sedimentation process, should be operated during the heavy rainfall season.

Evaluation of the DAF Process for High Turbid Water

In order to test the performance of the SWTP during the operating mode of the DAF PROCESS, high turbid water was intentionally injected into the DAF plant at a flow rate of 1,000 m^3/basin-hr, without the pre-sedimentation process. Water that was 8 m below the surface of the HS Lake was used for the high turbid water. The water characteristics are summarized in Table 3. The concentrations of turbidity at each experiment were 25.8 NTU at the first trial and 34 NTU at the second trial.

Table 3. Characteristics of the tested raw water

	Period	pH	Turbi.(NTU)	Alkal.(mg/L)	Zeta.P.(mV)
1st trial	’05.6.30.	6.81	25.8	12.7	−6.05
2nd trial	’05.7.01.	6.79 ~ 6.97	34	17.6 ~ 19.7	−11.79 ~ −8.76

[a]Each 20 min measurement during 15:00 ~ 18:00 (2005.06.30) and 15:00 ~ 18:00 (2005.07.01): pH, Turbidity, Alkalinity and Zeta Potential.

[b]All the samples were measured in duplicate.

In this experiment, the coagulation was performed prior to the DAF process with the doses of 15 mL/m^3 of coagulant (PAHCs) and 2 mg/L of lime. The recycle ratio of the saturator was maintained at 10%, while the pressure of the saturator was maintained at 5 kg/cm^2. The G value of the flocculator during the DAF process was 70 sec^{-1} in the first stage and 50 sec^{-1} in the second stage. The float scraper was operated at 45 mm/s (5 times/min). Figure 4 shows the results of these two experiments. Regardless of the initial concentrations of turbidity present in raw water, it was observed that there were high removal efficiencies (>92%) during the DAF process in both the first and the second experiments, yielding a low concentration of turbidity (0.2–2.6 NTU). This clearly demonstrated that the DAF process is able to reveal a sound treatment ability for the most problematic water from the source at the HS Lake. It was found that the DAF PROCESS operating mode is sufficient to provide for the production of safe drinking water at the SWTP. In addition, this result supported the trend in using the DAF treatment process for high turbid water that occurs during the heavy rainfall season. As mentioned previously (Fig. 3), a high turbidity of 430 NTU has always occurred during the heavy rainfall season. During heavy rainfall, a 16.5 NTU turbidity remained in the effluent of the pre-sedimentation process, which was less than the turbidity of water coming directly from the HS Lake, as shown in Table 3. This implies that the turbidity in the source water does not exceed the treatable capacity of the DAF process even during the heavy rainfall season. Therefore, it can be concluded that when the DAF process is integrated with the pre-sedimentation process, it is possible to control the specific raw water characteristics, which can often show an unexpected dramatic increase in turbidity.

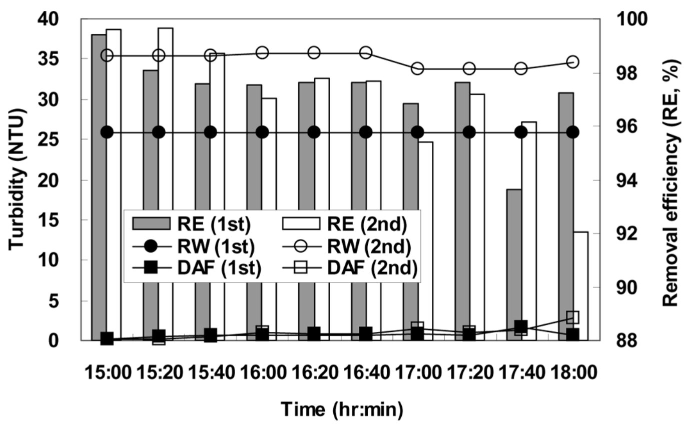


Figure 4. Removal efficiency of high turbidity by the DAF process.

Application of a Variable Weir for the DAF Process

In general, influent water in many DAF plants is operated at a fixed flow rate. The fixed weir is often utilized in the DAF process. However, since it is difficult to control the flow rate of influent water, a critical problem could arise in a DAF process when it is equipped with a fixed weir. For example, when the water level in the DAF basin was too low to be reached by the scraper, the floats could not be successfully removed. Also, when the high turbid water was introduced, the float could become heavy, forming a thick bed of float. Therefore, the low part of the float could not be easily removed due to the limitation of the moving distance of the scraper. In the case of the SWTP, the DAF process with the fixed weir hardly removed the float below the flow rate of 900 m^3/basin-hr. To solve this problem, a newly devised weir was suggested, called a "variable weir" and used in the SWTP from April 2004. Figure 5 illustrates the schematic of the DAF process equipped with the variable weir. The water level in the DAF basin was simply controlled through the height change of the variable weir. The variable weir can be pulled forward so that the water level increases towards the scraper. Figure 6 shows several photographs that illustrate the operation of this variable weir. Figure 6(a) shows how the gear handle is connected to the rack gear, while Figs. 6(b) and 6(c) show how the gear handle controls the height of the variable weir. Figures 7(a) and 7(b) compare the removal efficiencies of the turbidity and show that there is a difference of >15 μm particles removed between the DAF processes fitted with a variable weir- and that fitted with the fixed weir. At both tested parameters, the removal enhancements were observed by utilizing the variable weir. In particular, the removal efficiency of relatively heavy particles (>15 μm) was much higher when

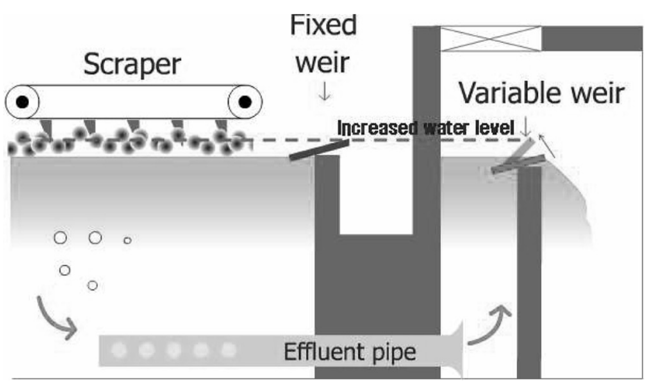
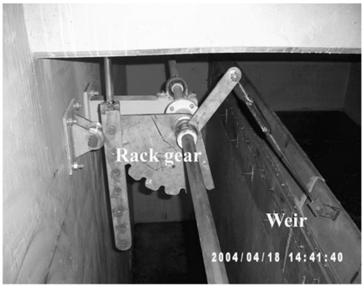
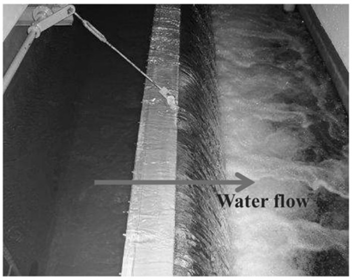


Figure 5. Schematic of the DAF basin equipped with the variable weir.

(a) Gear handle



(b) Rack gear and weir



(c) Variable weir

Figure 6. Photographs of the variable weir in the DAF basin.

the variable weir was used. This indicates that the DAF process equipped with a variable weir could prove to be an innovative tool used to solve the critical problem caused by the fixed weir. Actually, the range of the flow rate, at which the float can be easily removed, was changed from 900–1100 to 400–1100 m^3/hr.

Effect of PAC on the Performance of the DAF Process

Figure 8 shows the concentrations that were detected of the chlorinated by-products in the effluent of SWTP, such as total trihalomethane (THM), dichloroacetic acid and trichloroacetic acid (HAA2), and Chloral hydrate (CH). The detected chlorinated by-products were much lower than the regulated concentrations of each compound for standards in both Korea and USA (Table 4). Since the chlorinated by-products could be increased through the post-chlorination process, K water (Korea Water Resources Corporation) has attempted to reduce the level of chlorinated by-products by providing stronger regulations (K water GOAL in Table 4). In order to meet the treatment goal, powdered

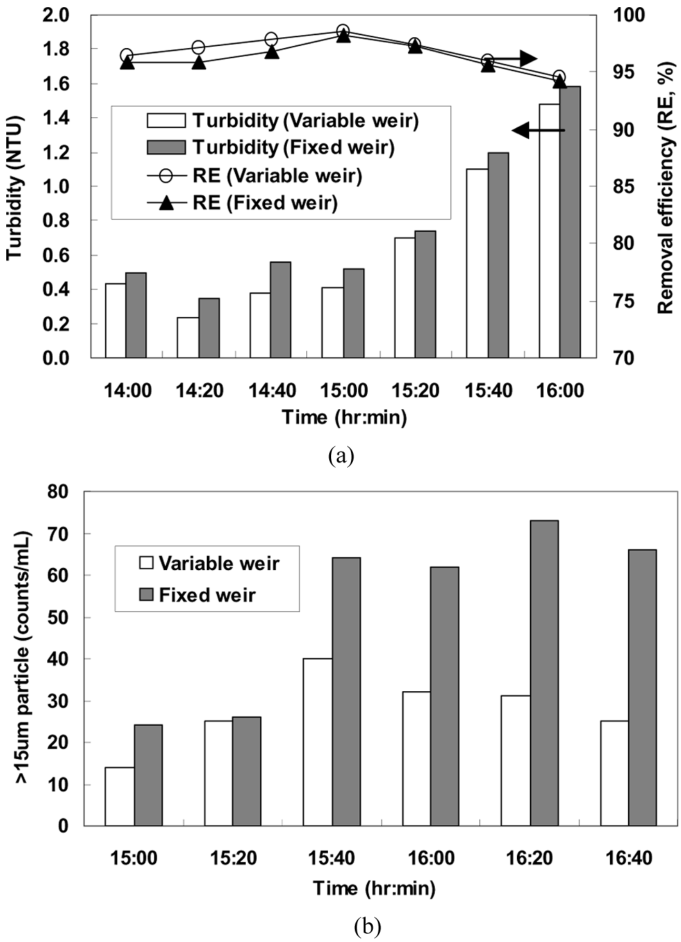


Figure 7. Effect of weir type (variable and fixed weirs) for the removal of turbidity (a) and > 15 μm particle (b) during the DAF process, flow rate = 1,050 m^3/basin-hr, saturator pressure = 5 kg/cm^2, recycle rate = 10%, float scraper condition = 45 mm/s.

activated carbons (PAC) were injected prior to the addition of coagulants. Table 5 summarizes the average concentrations during the period of April 2004 to March 2006 of chlorinated by-products detected in the effluent water of the SWTP, both with and without PAC addition. There was no difference detected between the concentrations of THMs and those of CH with and without the PAC addition. However, adding PAC reduced the HAA_2 to approximately 9 μg/L. This result concurs

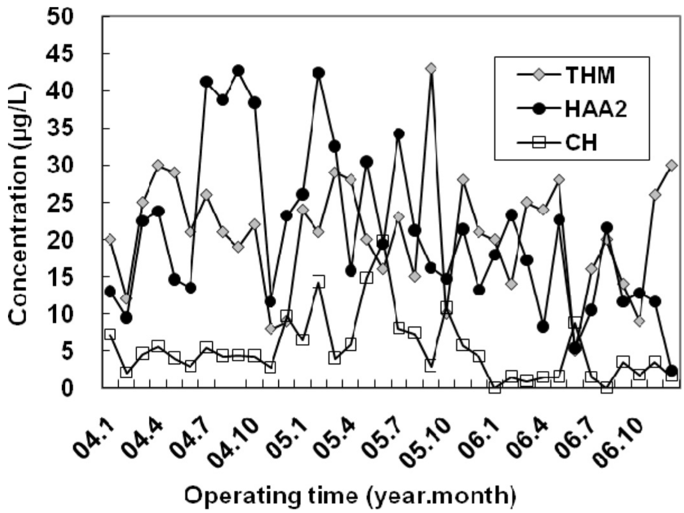


Figure 8. Concentration of chlorinated by-products in the effluent of the SWTP.

with the current problematic high levels of HAA_2 of chlorinated BPs in most of the Korean drinking water treatment plants. However, the increase of turbidity was observed in the effluent water of the pre-sedimentation process using PAC contactor, which was due to the addition of PAC (Table 6). Nevertheless, the DAF process still showed a sound efficiency in being able to reduce the turbidity, yielding only a slight increase level of 0.08 NTU in an average value for one year.

Cost-Effective Operation with a Variable Recycle Ratio

One of the main purposes for the variable operating mode in the SWTP is to provide a cost-effective operation for the SWTP. In terms of the

Table 4. Criteria of chlorinated BPs. (Unit : µg/L)

	Criteria in law		K water GOAL	
Parameters	KOREA	USA	Effluent of SWTP	End of pipe
THMs	≤100	≤80	≤64	≤80
HAA_2	≤100	≤60[a]	≤48	≤60
CH	≤30	–	≤24	≤30

[a]Hass.

Table 5. Concentrations of chlorinated BPs with and without PAC addition. (Unit = μg/L)

	w/o PAC addition			w/ PAC addition		
Parameter	THMs	CH	HAA_2	THMs	CH	HAA_2
Avg.	21.6	5.7	29.1	21.9	6.8	20.4
Max.	30.0	14.3	42.7	43.0	19.8	34.2
Min.	8.0	2.8	11.6	10.0	0.0	13.2

[a]Monthly measurement during 2004.04 ~ 2005.03: THMs, CH and HAA_2 without PAC addition.

[b]Monthly measurement during 2005.04 ~ 2006.03: THMs, CH and HAA_2 with PAC addition.

[c]All the samples were measured in duplicate.

cost-effective operation in the DAF process, an attempt was made to control the recycle ratio (a flow rate of the recycled DAF effluent divided by a flow rate of the DAF influent) according to the level of turbidity in the influent water of the DAF process. In the DAF process, the amount of microbubble is the key operating parameter to sufficiently remove the turbidity, which can be controlled by the pressure of the saturator or the recycle ratio (11). In the SWTP, the turbidity was controlled by changing the recycle ratio using two separate injection manifolds (pipe diameter = 150 mm for 6.6% of the recycle ratio and 100 mm for 3.3%). If the turbidity in raw water is higher than 10 NTU, the recycle ratio is

Table 6 Turbidity with and without PAC addition. (Unit = NTU)

	w/o PAC addition			w/PAC addition		
Parameter	Raw water	Pre-sedimentation effluent	DAF effluent	Raw water	Pre-sedimentation effluent	DAF effluent
Avg.	3.5	1.9	0.15	3.5	2.8	0.23
Max.	12.7	3.5	0.24	18.9	3.9	0.38
Min.	0.8	0.5	0.11	0.7	1.9	0.17

[a]Monthly measurement during 2004.04 ~ 2005.03: Turbidity without PAC addition.

[b]Monthly measurement during 2005.04 ~ 2006.03: Turbidity with PAC addition.

[c]All the samples were measured in duplicate.

maintained to be 10% of the DAF influent flow by using both injection manifolds. If the turbidity is less than 10 NTU, only one manifold (pipe diameter = 100 mm) is used to meet the recycle ratio of 6.6%. Figure 9 shows the values of turbidity in the effluent of the DAF process at two different recycle ratios. The removal efficiency of turbidity at the recycle ratio of 10% was approximately twice as high as that of 6.6%. It was because the increase of the recycle ratio provokes the enhancement of bubble volume concentration (BVC). The increase of the BVC ensures adequate collisions between the flocs and bubbles, resulting in the increase of removal efficiency of the flocs (12). Even though only two recycle ratio conditions were tested, it was found that the removal efficiency of turbidity increased concurrently with an increase in the recycle ratio. However, the electric energy cost was also raised from 0.178 for 6.6% to 0.225 €/m^3 for 10%. This indicates that the operating strategy, which is the variable recycle ratio according to the water quality of the DAF influent water, has a beneficial influence on the cost-efficiency of operating the DAF process. If the SWTP is operated under 6% recycle ratio for normal season (9 months) and 10% recycle ratio for the heavy rainfall season (3 months), approximately 26,000 $/year could be saved as compared to the operation with 10% recycle ratio all the year round.

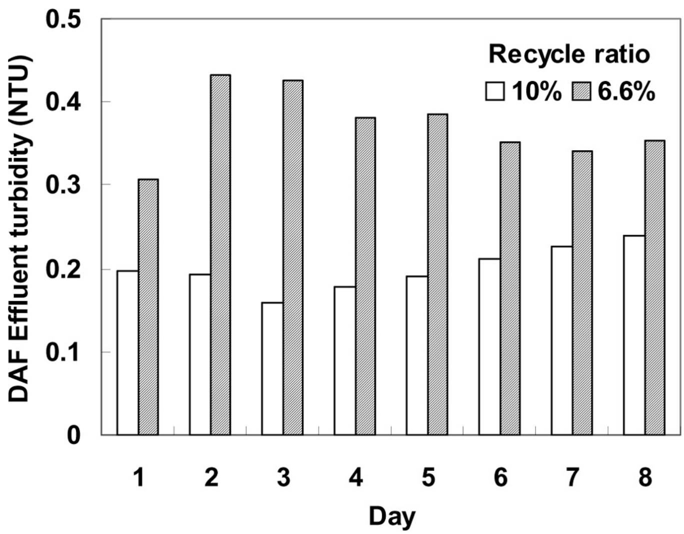


Figure 9. Turbidity in DAF effluent at different recycle ratio (10% and 6.6%), operating period = '05.11.28 ~ 12.05 with the recycle ratio of 10% (turbidity in influent water of the DAF process = 2.7 ~ 4.4 NTU), '05.12.28 ~ '06.01.04 with 6.6% (turbidity in influent water of the DAF process = 2.3 ~ 3.3 NTU).

CONCLUSIONS

A case study was carried out to evaluate the dissolved air flotation (DAF) process installed in the Songjeon drinking water treatment plant (SWTP). During 2004 to 2006, even in a heavy rainfall season, the DAF process, when integrated with the pre-sedimentation process, provided productive water with a low and stable water quality, yielding the turbidity concentration of 0.15–1.16 NTU. The pre-sedimentation process played an important role in eliminating heavy particles, which can damage the DAF process.

The DAF process revealed a sound performance for the treatment of high turbid water (turbidity $= 25.8 \sim 34$ NTU) caused by source water (HS Lake) for the SWTP. It could be suggested that the operating mode of the FULL PROCESS, including pre-sedimentation and DAF, should be selected during the heavy rainfall season, and that the DAF PROCESS mode is sufficient to treat the HS Lake source water during the other period. This indicates that the alterable operating mode in the SWTP is a promising technique to control the specific raw water characteristics, which can show unexpected dramatic increases in turbidity. To replace the fixed weir, a newly devised weir called the "variable weir" was applied to the DAF process in order to improve the float removal efficiency of the scraper. Utilizing the variable weir resulted in the removal enhancements of turbidity and the removal of $>15\,\mu m$ particles. It also facilitated an increase in the flow rate range at which the float can be easily removed, from 900–1100 m^3/hr to 400–1100 m^3/hr. Even though the addition of the PAC caused an increase of turbidity, there was no significant influence in the DAF process. This still showed a sound efficiency of turbidity removal.

In addition, the two injection manifolds (pipe diameter = 150 mm for 6.6% of recycle ratio and 100 mm for 3.3%) were tested in the DAF process in order to change the recycle ratio. Even though the increase of turbidity removal efficiency was observed when the recycle ratio increased, the electric energy cost was also raised. This indicates that the recycle ratio in the DAF process should be selected by considering both the removal efficiency of turbidity and the operating energy cost, according to the turbidity level in the influent water of the DAF process.

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