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A case study on the automatic ozone dose control system based on the ozone decay rate in a full-scale advanced water treatment plant

Jei-cheol Jeon[a,c], Chang-Hyun Jo[a], Soon-Buhm Kwon[a], Kyung-Hyuk Lee[a],
Tae-Mun Hwang[b,c]*, Yonkyu Chung[c]

[a]*Korea Water Resources Corporation, San 6-1 Yonchook-dong, Deadeok-gu, Deajeon-si 306-711, Korea*
email: jcjeon@kwater.or.kr
[b]*Korea Institute of Construction Technology, 2311 Deahwa-dong, Ilsan-gu, Goyang-si, Kyonggi-do 411-712, Korea*
Fax +82 (31) 910-0741; email: teamun@kict.re.kr
[c]*Department of Civil & Environmental Engineering, College of Engineering, Yonsei University, Seoul 120-749, Korea*
Tel. +82 (31) 910-0741; Fax +82 (31) 910-0291; email: taemun@kict.re.kr, choung@yonsei.ac.kr

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ABSTRACT

Recently, a growing concern about algae-origin taste and odor in drinking water made it possible to introduce ozone and granular activated carbon (GAC) processes to large-capacity (more than 300,000 m^3/d) water treatment plants in the Han River area in South Korea. Especially, concerning the ozone process, the ozone residual of ozone contactor effluent may affect on the biological destabilization, poor physical properties of the following GAC process and operators' health due to high ozone gas concentration in GAC contactor. Therefore, maintaining an optimal ozone dose based on the ozone demand is essential to the operation of the ozone process. The Koyang Advanced Water Treatment Plant (KAWTP) has been utilizing a new type of ozone control method since July 2009, which automatically calculates required ozone dosed based on the instantaneous ozone demand (ID) and the ozone decay rate constant (K_c). The ID and the first-order K_c values are calculated based on the measured dissolved-ozone concentrations from at least three points of ozone contactor. After the calculations of ID and K_c values, the values were applied for the proportional integral derivative (PID) ozone dose control system. PID control is operated through two different methods. The first involves automatic controlling the ozone dose, by which the ozone residual of the effluent from the ozone contactor will be maintained at the desired value set by the operator. The second method was the modified extended CSTR method, which was appropriately modified to fit the KAWTP site specifications, to calculate the *Cryptosporidium*, *Giardia* and virus log inactivation automatically. An automatic ozone dose control system based on the ozone decay rate overcomes the disadvantages of the previous ozone control systems, including late response and variation of effluent ozone residual. In the earlier pilot scale research, an extra device for measuring K_c and ID was used. In this study, the ozone dose was determined by measuring K_c in the full-scale ozone process. It is the first case in Korea that applied ID-K_c-based ozone dose control to a full-scale water treatment plant. According to the operation results of the automatic ozone dose control system based on K_c calculation, adequate-ozone-dose calculation along with the various water quality and inflow rate was performed successfully, and the ozone residual of the effluent was also maintained below the lowest set value during operation. Moreover, the process was adequately run to maintain the target

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* Corresponding author.

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log inactivation the *Cryptosporidium*. Also, calculating the optimal ozone dose that could completely oxidize ozone-consuming matters and leave minimum residual, could be economical due to excessive ozone dose saving, and the biological and physical stability of GAC granule in GAC process.

Keywords: Ozone; Automatic control; ID (instantaneous ozone demand); K_c (ozone decay rate constant); Full-scale

1. Introduction

Koyang Advanced Water Treatment Plant (KAWTP), located in Koyang, South Korea, has been providing the cities of Koyang and Paju and the surrounding areas with tap water since July 2009, with its capacity of 350,000 m^3/d. KAWTP has introduced an advanced water treatment system that utilizes ozone and GAC, in order to remove recalcitrant taste- and odor-causing substances (2-MIB and Geosmin). The water treatment process at KAWTP is as shown in Fig. 1, and it consists of a stilling basin – pre-chlorination – mixer – flocculation/sedimentation basin – rapid filtration – ozonation – GAC – post-chlorination water treatment process, and adjustment – concentration – dehydration waste water treatment process. For the advanced water treatment system, ozonation and the GAC process has been introduced, and the specifications of the processes are as shown in Table 1. The side stream injection method is used for ozone dissolution. The ozone transfer efficiency has been found to be above 98%. Automatic proportional integral derivative (PID) control using the ozone decay rate constant (K_c) and instantaneous ozone demand (ID) were applied for ozone dose control, which is the first full scale case in Korea. Its application method has also been improved in that previous research used feedback method that calculated K_c and ID with a separate external device and then re-applied these values to the ozone dose calculation process [1]. The new method is a feedforward method that instantly calculates K_c and ID within the ozone contactor and applies them directly to the ozone doses to maintain a desired dissolved ozone concentration. It can also obtain real-time samples at three different points depending on the retention time in the ozone contactor, without a separate device, and can draw ID and initial dissolved-ozone concentration (C_0) by calculating K_c. Then, by applying these values to the process, the new system automatically set the initial ozone dose so that the ozone residual of ozone reactor effluent reaches the set value (practically below 0.1 mg/L). Log inactivation of *Cryptosporidium, Giardia,* and virus can also be automatically calculated in another mode using the modified extended CSTR method, and the ozone dose is automatically chosen based on the *Cryptosporidium* standard, which has the lowest log inactivation value among three microorganisms.

The ID and the second half-life of the ozone measurement method were first proposed by Hoigné and Bader in 1994 [2]. When ozone is dissolved in water, it undergoes a two-step reaction process, the rapid ozone decay step, and the rather slower decay step. Of these, the first step (the rapid decay step right after injection) is defined as the ID, and the next step is defined as the ozone decomposition rate. Normally, the ID value is the 25–50% reduced concentration from ozone dose, and the

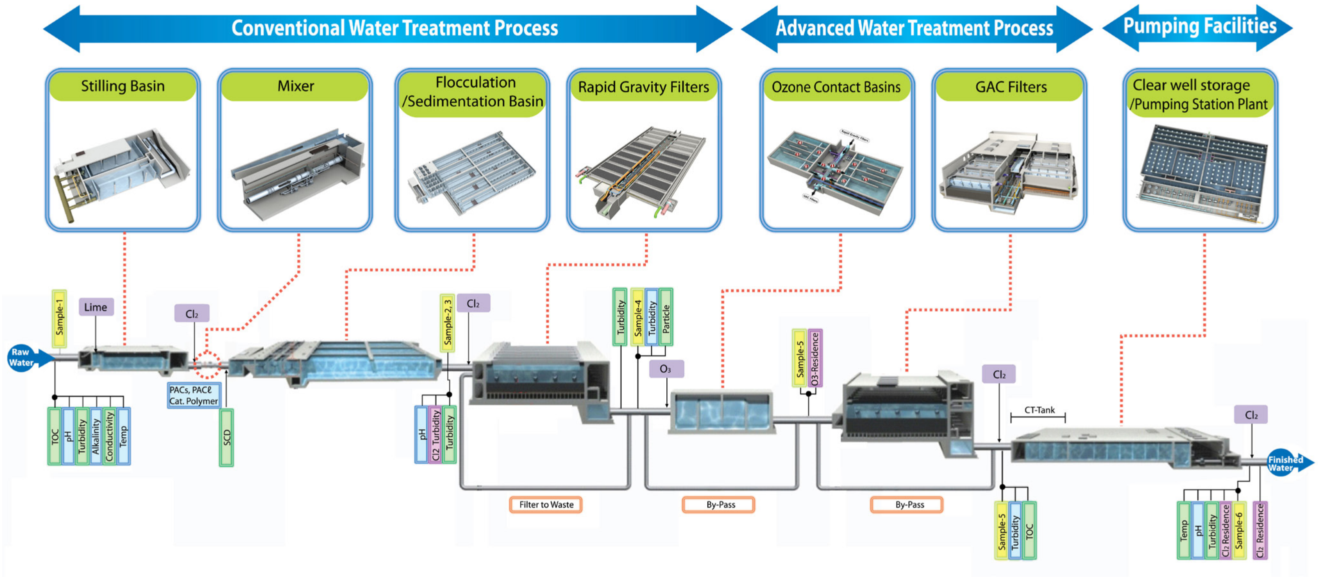

Fig. 1. KAWTP treatment train.

Table 1
Ozone facility specifications

Process	Items	Specifications
Ozone process	Reactor tank specifications	B 18 m × L 18.2 m× H 6.0 m × 2 tanks (retention time: 15.4 min)
	Ozone dose	0.5–2.0 mg/L
	Oxygen supply	Liquid oxygen type: 10.5 kg/h × 2
	Ozone contact type	Side stream injection
	Ozone-dissolving equipment	Main dissolving pipe: D 1,650 × 9.0 m × 1; ejector: 150 A × 4; mixing nozzle: 8
	Air-compressing equipment	Reciprocating air compressor: 0.3 Nm3/min·9.9 K, air dryer, after-cooler, nitrogen supply device, single equipment
	Motive pump	Q4.4 CMM × 24 mH × 4 (level 1)
	Discharged ozone gas removal equipment	Thermal-decomposition catalyst type: 300 m3/h × 3
	Pipes and valves	Pipe/ valve: SP+ internal coating/SSC14
	Water and corrosion resistance	Ozone resistance type (silicate coated apply, UGA)

ozone decomposition rate follows first-order kinetics. The ID, the first-order ozone decay rate constant (K_c), and the ratio of OH· exposure to O_3 exposure (R_{ct}) were measured under several water conditions to characterize raw water in the ozonation process. Hoon-Soo Park et al. [1] used a specific experiment device capable of automatic sampling and continuous analysis of the ozone residual to determine the ID, K_c, and R_{ct}. They also analyzed the fate of OH· during the slower ozone decay phase, and of OH· during the rapid ozone decay phase. Even though when ozone decay rate was modeled and estimated by Westerhoff et al. [3], the standardization of the factors determining the ozone decay characteristics, such as ID and K_c, can not be obtained because water quality varies based on how much ozone-consuming matters exists in the water. Therefore, they are rarely applied to real water treatment processes. Moreover, for application to the full scale water treatment processes, the analysis of the ozone decay characteristics had to be done quickly, and if possible, in real time. These requirements were fulfilled in the new method that measures K_c and ID, without a separate device.

2. Materials and methods

2.1. System configuration

The automatic ozone dose control method by the ozone decay rate is based on the dissolved ozone concentration readings measured at several different points. Total of seven sampling ports were installed into the ozone reactor tank at KAWTP. The location of sampling points is as shown in Fig. 2. One of points 1–3, point 4, and one of points 5–7 are connected to respective dissolved ozone-measuring instruments, so that the operator can choose three sampling points among 7 points by adjusting the valves. The ozone dose required to maintain desired ozone residual is then automatically calculated with an Excel-based program based on the readings from the dissolved ozone-measuring instruments. What is important here is the calculation of the retention time at each sampling point. The calculation method for the retention time will be dealt with in the following section.

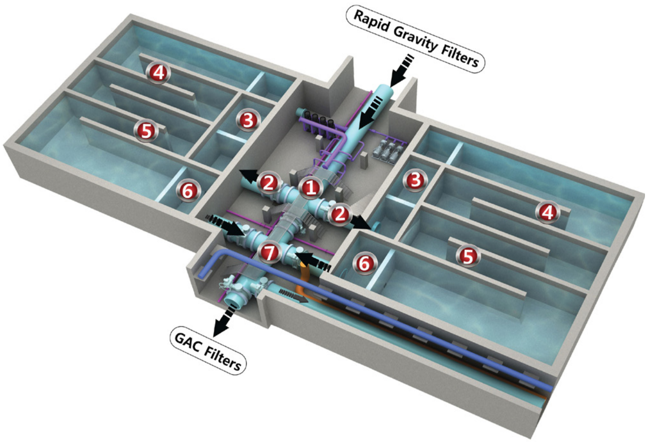

Fig. 2. Sampling positions within the ozone contactor.

Model IN-2000-L2-LC-W1 of IN USA, Inc. (USA) was used for the ozone measurements. This measuring instrument consists of a transfer column and a UV analyzer, and it uses the transfer of ozone from the liquid to the gaseous phase for absolute determination based on UV absorption, and continuously measures the ozone concentrations in the liquid phase. It uses the stripping column method with an advanced electronics design to deliver highly accurate and stable readings of dissolved ozone concentration. The measurement range was 0.01–5.000 mg/l, the precision/repeatability was 0.01 mg/l, and the resolution was 0.01 mg/l.

2.1.1. Calculation of the retention time

To calculate the retention time within the ozone contactor, the depth of the inflow water was calculated. The water depth was calculated using Eq. (1). The concept of retention time calculation is summarized in Fig. 3.

$$H = W + h \tag{1}$$

where H is total depth, W — Weir depth and h — flow depth. Here, the flow depth (h) was calculated as a function of the inflow water volume (Q) and the Weir flow coefficient (C), and for the flow coefficient $C = F(Q)$ relation, Ishihara and Ida's equation for width Weir [Eqs. (2) and (3)] was used.

$$Q = CBH^{3/2} \tag{2}$$

$$C = 1.785 + \left(\frac{0.00295}{h}\right) + 0.237\frac{h}{W}(1+\varepsilon) \tag{3}$$

Hence, final-outflow Weir width $B = 4.2$ m; W = outflow Weir depth (16.24 m) – floor depth (10.70 m) = 5.54 m; and therefore, $\varepsilon = 0.55\ (W-1) = 2.497$. Therefore, when these figures are substituted into Eqs. (2) and (3), Eqs. (4) and (5) will be obtained.

$$Q = 4.2Ch^{3/2} \tag{4}$$

$$C = 1.785 + \left(\frac{0.00295}{h}\right) + 0.237\left(\frac{h}{5.54}\right)(1+2.497) \tag{5}$$

Based on these, the water flow and flow coefficient for an arbitrary flow depth h at arbitrary intervals were calculated, and the relation [Eq. (6)] for the inflow water volume was drawn at a section C, where the flow depth is at least 0.2 m.

$$C = 5E^{-6} \times Q + 1.8175 \tag{6}$$

When Eq. (6) was compared with the basic Weir width equation throughout all the sections, the uncertainty was calculated to be 0.01–0.04%, which proved that the relation was valid. The ozone contactor water depth calculation involved the following three steps: (1) calculation of the flow coefficient (C) based on the flow rate of influent and Eq. (6); (2) calculation of the flow depth using Eq. (4); and (3) the total-depth (H) calculation using Eq. (1). The system was then organized to automatically calculate the retention time for different flow rates based on the sectional volume calculated from the sectional area and the calculated total depth.

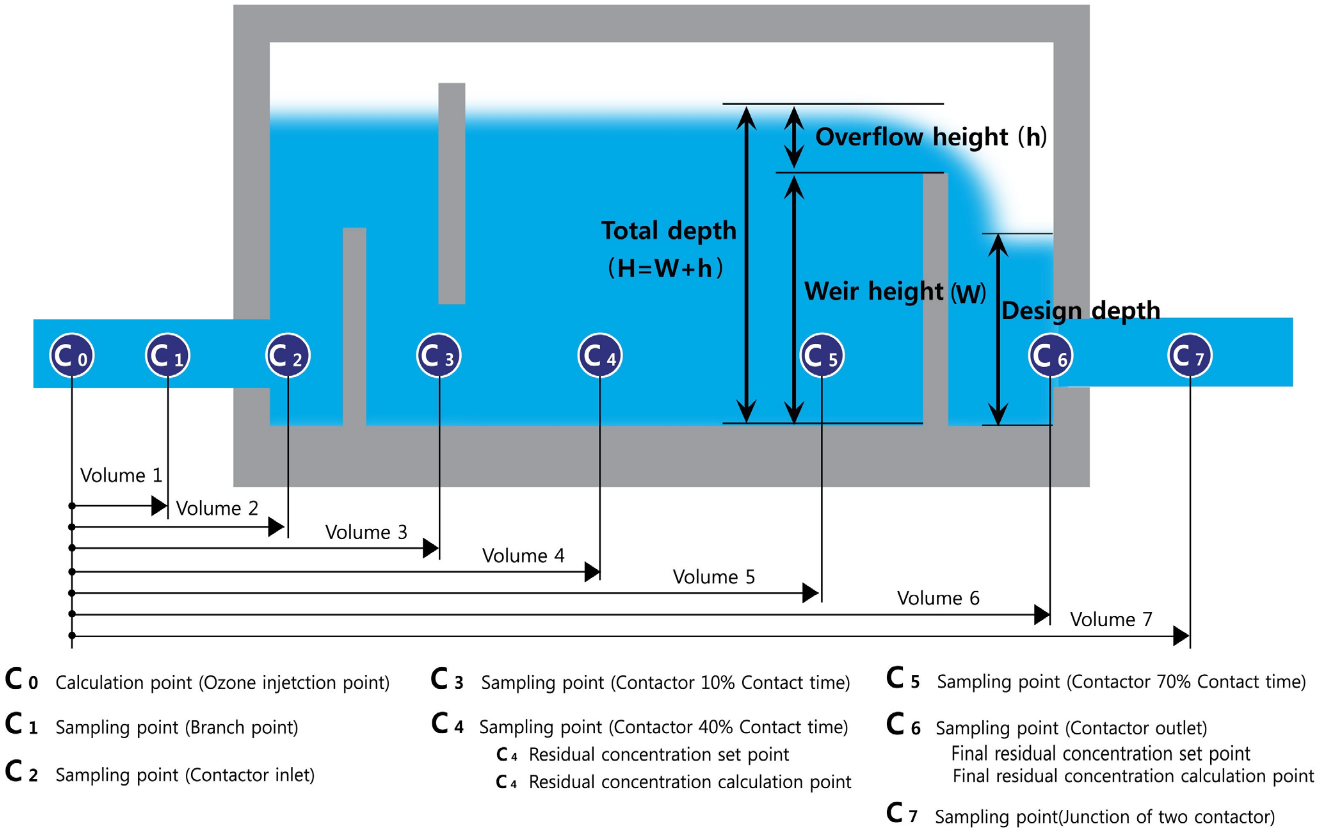

Fig. 3. Diagram for retention time calculation.

2.2. Mechanism of ozone dose control based on ozone decay

The basic concept of the ozone dose control based on ozone decay is as shown in Figs. 4 and 5. As shown in these figures, the ozone decay rate constant K_c can be calculated from the dissolved ozone concentration and the retention time at two points. Therefore, by taking the measurements at three points, two K_c values can be calculated, and of the calculated K_{c1} and K_{c2}, either the average value of K_{c1} and K_{c2} or one of the two values, will be automatically selected and used for control. Once the K_c value to be applied is chosen, this K_c value will be used to calculate C_0, and from C_0, the ID will be calculated. Once the K_c, C_0, and ID values are calculated, the program will then be able to automatically calculate the expected ozone concentration at each sampling position, and finally, to calculate the ozone residual of the effluent from ozone contactor. If this calculated ozone residual of the effluent is different from the final ozone residual level set by the operator (maximum: 0.1 mg/L), the system will automatically change the ozone dose so that the ozone residual will be closer to the desired level set by the operator. Various factors, including K_c, were calculated using the following equations:

$$kc\ (\mathrm{min}^{-1}) = \ln\left(\frac{C_{i+n}}{C_i}\right) / \left(T_{i+n} - T_i\right) \qquad (7)$$

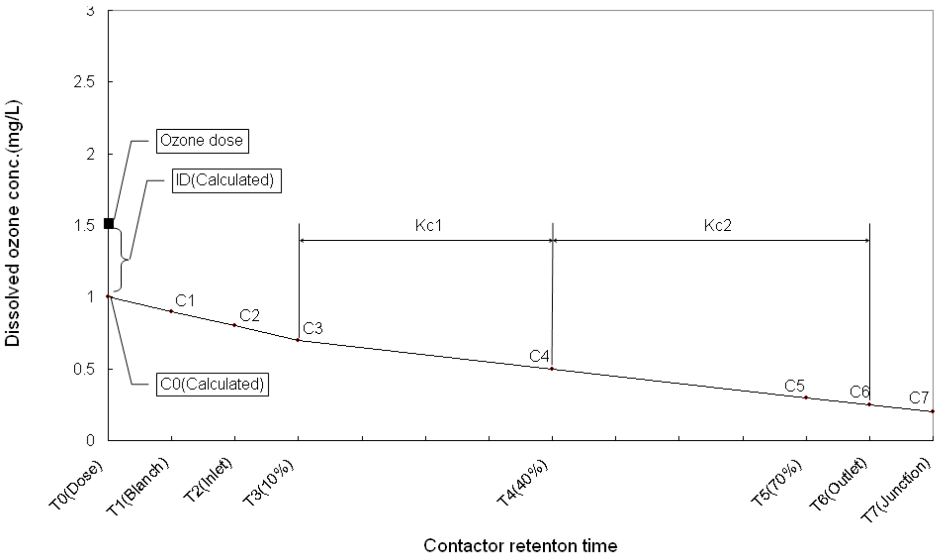

Fig. 4. Basic concept of the calculated ozone control mechanism.

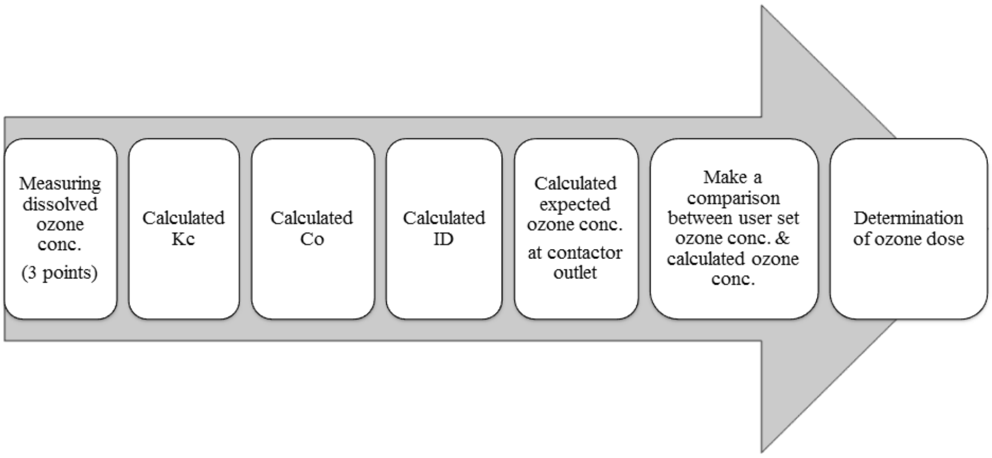

Fig. 5. Ozone process control sequence.

$$\therefore C_i = C_{i+n} / \exp\left[k_c \times \left(T_{i+n} - T_i\right)\right] \tag{8}$$

$$\therefore C_0 = C_6 / \exp(kc_2 \times T_6) \quad \text{or } C_0 = C_4 / \exp\left(kc_1 \times T_4\right) \tag{9}$$

$$ID = C_{input} - C_0 \tag{10}$$

2.3. Modified extended CSTR method

The modified extended CSTR method is the same as the conventional extended CSTR method in that it uses three consecutive ozone concentration monitoring points to calculate the average ozone decay coefficient (k*) and the dissolved ozone concentration at the injection point (C_{initial}). The standard equation for the extended CSTR method, however, is made to fit the flow of the ozone contactor, where only a co-current and a countercurrent are constantly formed, so it cannot be directly applied to the KAWTP ozone contactor, where there are not only a co-current and a countercurrent but also horizontal currents. The modified extended CSTR method for KAWTP was developed in this research to apply the extended CSTR to any type of ozone contactor.

The *Cryptosporidium*, *Giardia*, and virus log inactivation evaluation logic is organized by first calculating the ID, C0, and sectional K_c values from the measured ozone residuals and flow rate, and then making a *Cryptosporidium*, *Giardia*, and virus log inactivation table for the dissolved ozone concentration per unit water temperature and per unit time, which is composed from a table of dissolved ozone concentration C_i per time segments of one minute or below, and finally adding all the credit values within the contactor. The basic equation used for the logic is shown below:

$$\text{log inactivation} = \log\left(1 + 2.303 \times \Delta T_{i(\min)} \times C_i \times k_i\right) \tag{11}$$

The K values for the different microorganisms are calculated using Eqs. (12), (13) and (14).

$$\textit{Crypto } K_c = 0.0397 \times \left(1.09757^T\right) \tag{12}$$

$$\textit{Giardia } K_g = 1.038 \times \exp\left(0.0714 \times T\right) \tag{13}$$

$$\text{Virus } K_v = 2.174 \times \exp\left(0.0701 \times T\right) \tag{14}$$

where T is temperature (°C). The ozone dose is determined based on the *Cryptosporidium* inactivation credit, which has the lowest value. The application procedure is as follows:

- Step 1: For the sectional K_c and ID values evaluated, calculate each *Cryptosporidium* log inactivation value when ozone dose is changed by 0.1 mg/L.
- Step 2: Based on the results of step 1, the ozone dose is adjusted by 0.01 mg/L around the *Cryptosporidium* log inactivation criteria (the *Cryptosporidium* log inactivation value is the sum of all the credit values. Since it can deviate much from the target value due to the small differences in doses, it is designed to be controlled by the minute changes in the ozone doses).

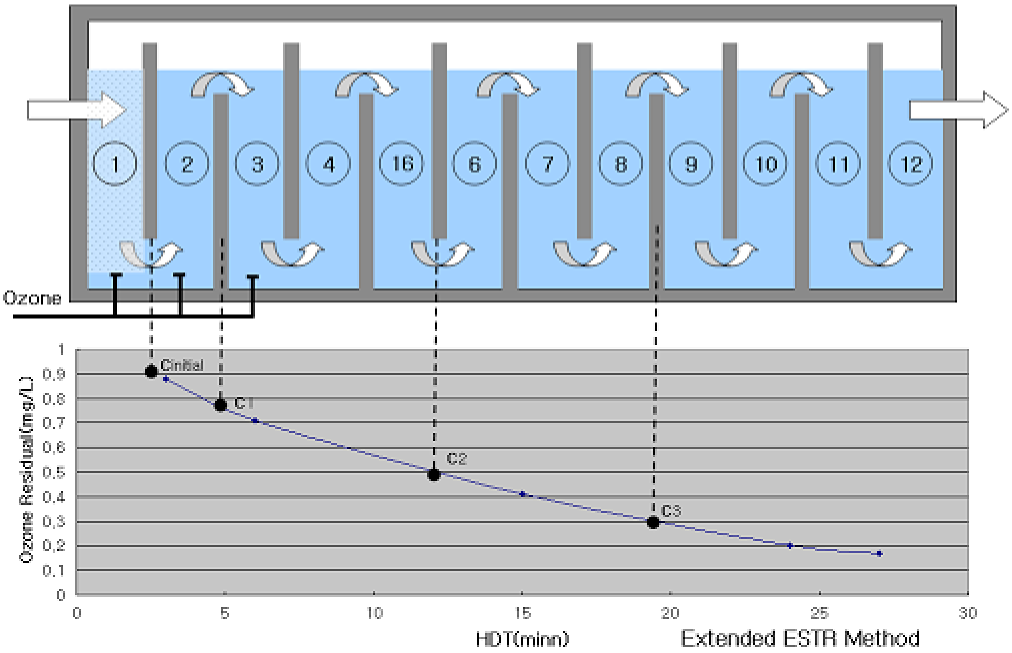

Fig. 6. Conceptual diagram of the extended CSTR method.

The ozone dose is automatically determined through the two-step calculation mentioned above, and if the current dose is different from the ozone dose set by the ozone control system, the system will automatically change the existing dose into the new dose.

2.4. Application of the ozone process

The modified extended CSTR method can be used for official disinfection credit in the US. However the legal criteria for acquiring *Cryptosporidium* inactivation have not yet been established in South Korea, so that the application of this method is currently still unofficial. Therefore KAWTP ran most of time its ozone processes using the ozone dose control based on ozone decay that could maintain the target ozone residual. When the modified extended CSTR method was tentatively used, it was found that the ozone control system run well based on *Cryptosporidium* inactivation. Ozone residual was found to be mostly around 0.1 mg/L, satisfying KAWTP's operating criteria in the extended CSTR method, too.

3. Results and discussion

3.1. Initial operation results

The operation of KAWTP's ozone process began in August 2009. The operation results of the ozone process are shown in Fig. 7. During the initial operation of KAWTP's ozone process, its automatic dose control system was not stabilized. Due to the failure of setting the optimum control factors, there were cases in which the first ozone residual was higher than the ozone dose; the terminal third ozone residual also deviated from the set value (below 0.1 mg/L), and a maximum of 0.757 mg/L was detected. Such problems were inevitable because minimal amount of ozone produced from the ozone generator(capacity: 10.5 kg/h) could not be reduced below 2.4 kg/h so that ozone dose control system based on ozone decay constants could not effectively maintain ozone contactor effluent residual below 0.1 mg/L.

3.2. Operation stabilization phase

After the initial trial-and-error phase, the ozone process began to be stabilized from September 24. Fig. 8 shows the results of its operation from September 24 to October 12. After October 12, the process was halted for about two weeks due to minor maintenance, and after that, a sudden drop in the flow rate (from an average of 4000 m^3/h to an average of 2500 m^3/h) caused higher final ozone residual because even when the minimum amount of 2.4 kg/h produced by the ozone generator was injected, the actual ozone dose was still above 1 mg/L, which is much higher than regularity, such problems are expected to end, when there will be a large increase in the flow rate due to supply to a new distribution system. The ozone

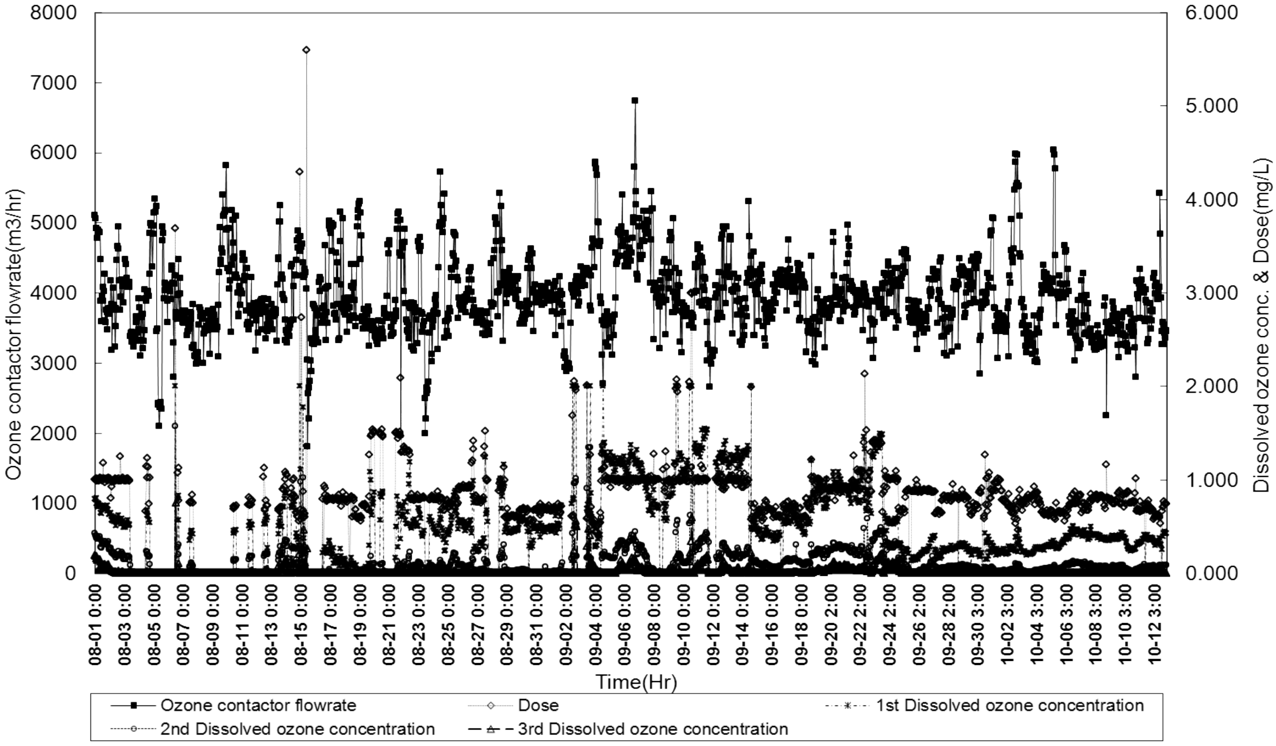

Fig. 7. Initial operation results of the KAWTP ozone process (initial stage to October 12).

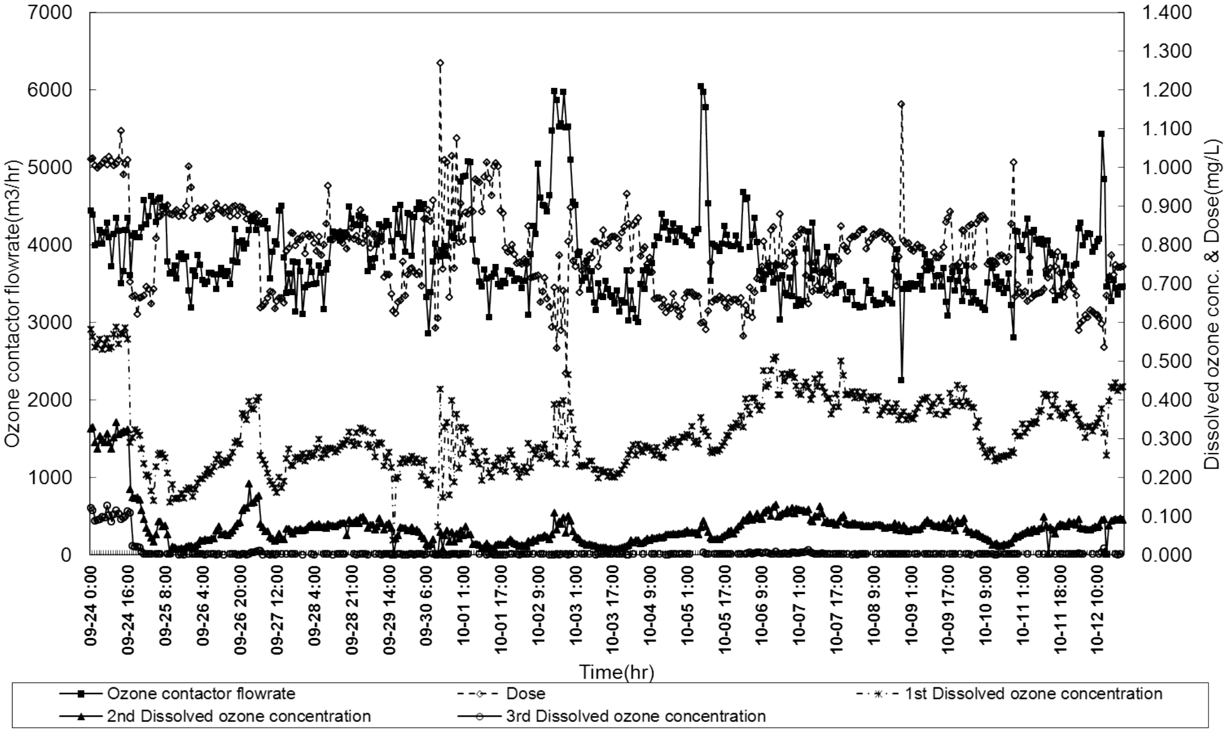

Fig. 8. KAWTP ozone process operation results (September 24–October 12).

dose during this period was automatically determined through the calculated ozone decay constants. The ranges of applied ozone dose during operation period were 0.468–1.269 mg/L (average 0.78 mg/L). The final third ozone residual concentrations were 0.001–0.128 mg/L (average 0.008 mg/L). Although, in several times, the residual ozone concentrations were higher than the target value of 0.1 mg/L, as shown in Fig. 8, mostly the residual ozone concentrations were below 0.1 mg/L, successfully. Moreover, the average deviation between the first and second ozone residual was 0.241 mg/L, and the average deviation between the second and third ozone residual was 0.064 mg/L, which show that most ozone-consuming matters reacted with ozone within 40% of the ozone contactor.

3.3. Ozone decay rate constant (K_c)

Regarding K_c calculated using three different dissolved ozone-measuring instruments, K_{c1} usually have a larger value than K_{c2}, because the ozone-consuming matters usually reached with ozone at the earlier stage rather than at the later stage. However, there could be a situation in which refractory matters require more contact time with ozone for decomposition. Therefore, the system is designed to determine appropriation of K_c value. If one of K_{c1} and K_{c2} values was out of the 20% deviation of average value, K_{c1} value was chosen as K_c. Otherwise average value of K_{c1} and K_{c2} was applied for K_c value. The calculated values of K_{c1} and K_{c2} during the normally controlled period are shown in Fig. 9. It was shown that after dose control was stabilized, K_{c1} became larger or similar to K_{c2}, and only occasionally was K_{c2} larger than K_{c1}. It was also shown that K_{c1} had little fluctuation, and the change in its value due to the variation of the water quality was gradual, whereas K_{c2} showed much fluctuation and instability. The overall trends of the two values were stabilized over operation time. Since October 2009, K_{c1} and K_{c2} have had similar values, meaning that the oxidation of ozone-consuming matters happens throughout the entire ozone reactor tank. The fluctuations of the K_{c2} values, are believed to be due to the deviation in the calculated results based on the third dissolved ozone concentration, which was operated at almost 0, or at a minimum of 0.0005 mg/L and an average of 0.008 mg/L. Thanks to the optimal operation of calculated ozone control, the third ozone residual was sometimes below the limit of the measuring instrument, causing the measured value to be 0 mg/L. Therefore, the system's variables were modified to control the process by determining whether the deviation between K_{c1} and K_{c2} is normal.

3.4. Initial dissolved ozone concentration (C0) and ID

The changes in the C_0 and ID values calculated from K_c are shown in Fig. 10. The initial dissolved ozone concen-

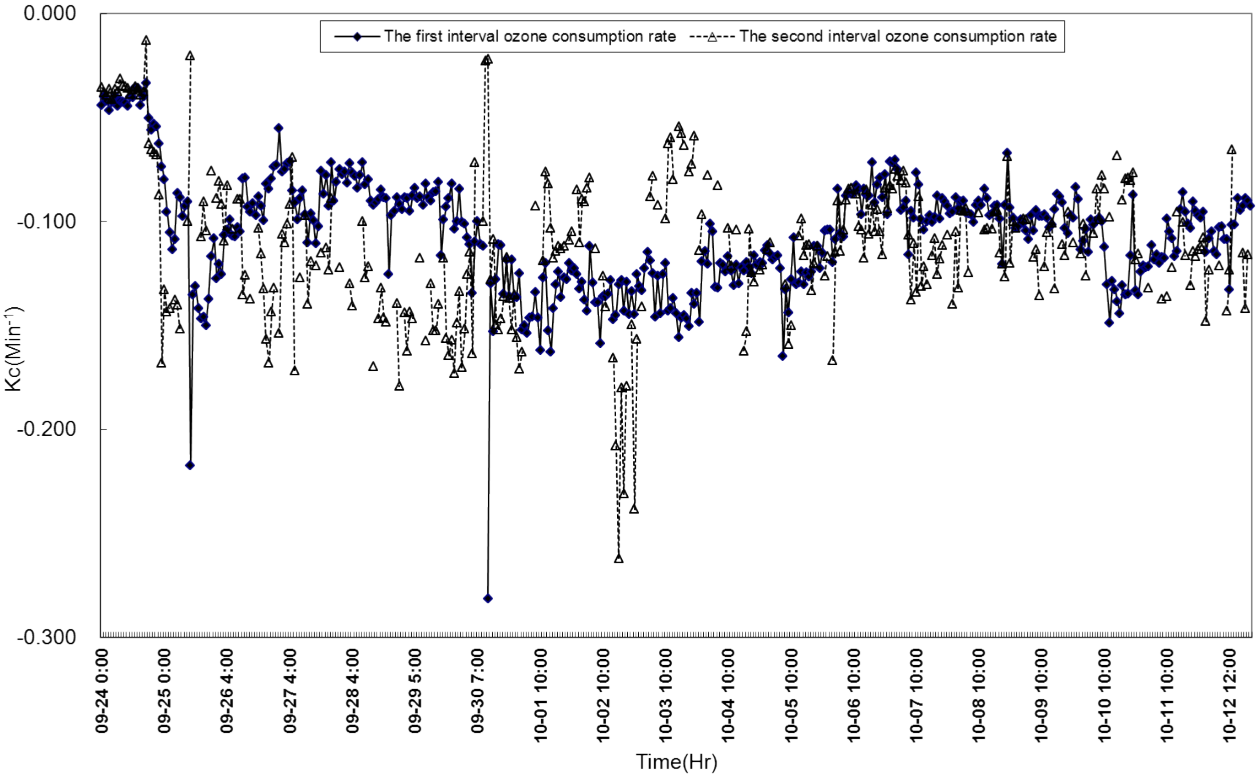

Fig. 9. KAWTP K_c calculation results (September 24–October 12).

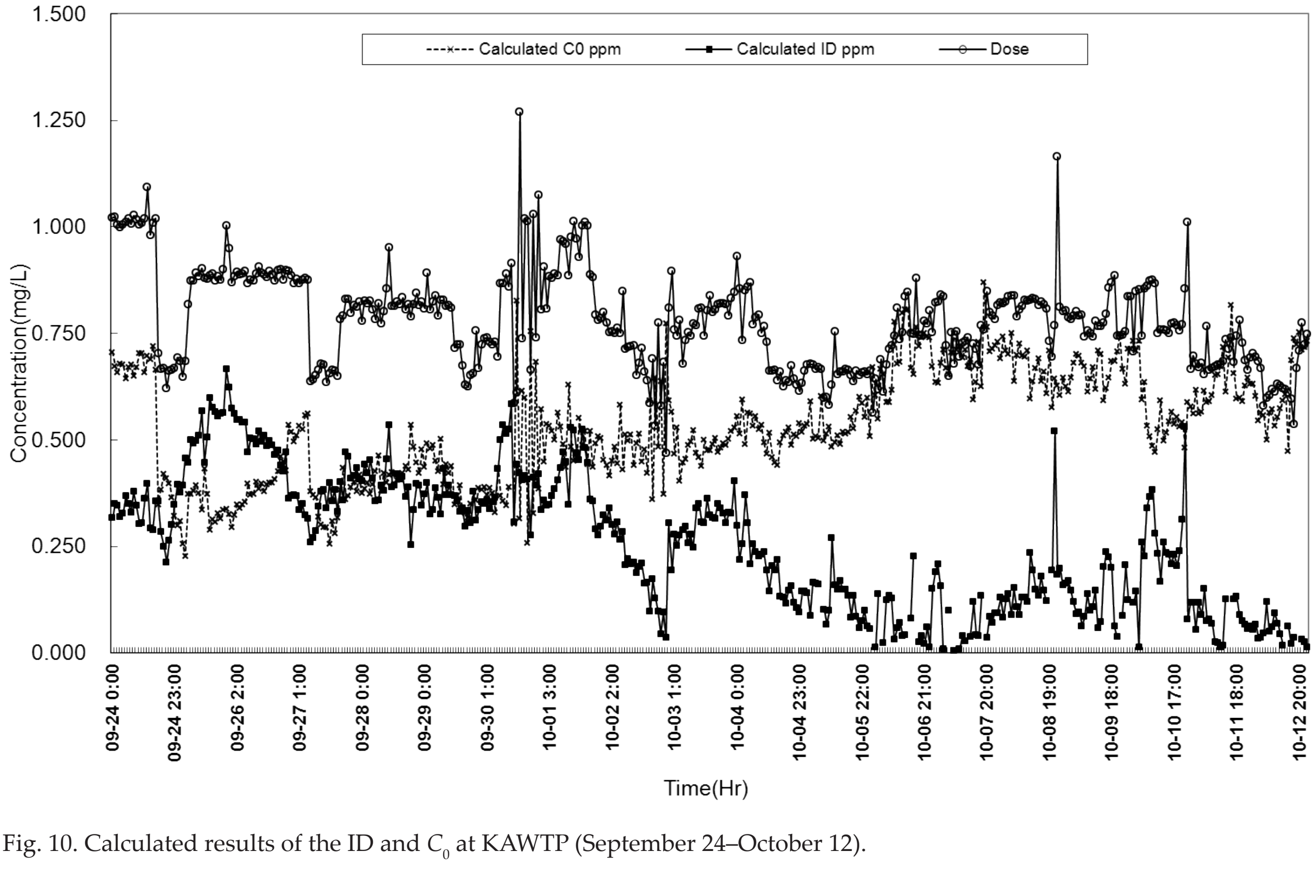

Fig. 10. Calculated results of the ID and C_0 at KAWTP (September 24–October 12).

trations (C_0) during this period were 0.531 mg/L (average), 0.87 mg/L (maximum), and 0.227 mg/L (minimum); the ID values were 0.262 mg/L (average), 0.666 mg/L (maximum), and 0.0045 mg/L (minimum); and the ozone doses were 0.781 mg/L (average), 1.269 mg/L (maximum), and 0.468 mg/L (minimum). What is noteworthy here is that at the point where the initial dissolved ozone concentration began to rise and the ID began to fall, K_{c1} and K_{c2} began to show similar patterns. Therefore, when the ID is high, which means that there are matters that react instantly with ozone, K_{c1} is larger, and as ID decreases, K_{c1} becomes smaller than K_{c2}, or their deviation becomes smaller. This means that K_c, C_0, and ID change according to the ozone-reacting characteristics of ozone-consuming matters, and that the change of the characteristics of these three factors reflects the characteristics of the ozone-consuming matters in the inflow water. Regardless of the circumstances, the ozone was applied to maintain residual ozone concentration "nearly zero" at the effluent of ozone contactor. This operation method would result in optimum oxidation of organic matter and prevent biological activated carbon (BAC) process from deterioration of GAC physical properties and bio organism.

3.5. Comparison of the estimated value and real process (1)

Fig. 11 shows the dissolved ozone concentration measured at the fourth sampling point, and the dissolved ozone concentration at the fourth point estimated with the K_c, C_0, and ID values calculated based on three ozone residuals measured. As shown in the figure, the estimated values almost perfectly match the actual measured values. Therefore, these results suggest that the ozone control system enable to control desired residual ozone concentration with 40% of inflow water flow rate variation. This also means that the operator can control the ozone residual at the desired position.

3.6. Comparison of the estimated value and the real process (2)

Fig. 12 shows the estimated ozone residual and the actual measurement of the effluent. Unlike at the second sampling point, the final ozone residual were 0.008 mg/L (average), 0.128 mg/L (maximum), and 0.0005 mg/L (minimum), whereas the estimated values were 0.019 mg/L (average), 0.12 mg/L (maximum), and 0.00002 mg/L (minimum), which are different from the actual measurements. The actual ozone process operation target value, was 0.1 mg/L, and after the calculated ozone control system was stabilized, most estimations estimated the dissolved ozone concentration to be below 0.1 mg/L, and the actual measurement of the ozone residual was also mostly below 0.01 mg/L. Therefore, it was shown that the ozone residual is controlled almost perfectly with calculated K_c. It can be deduced based on all the results

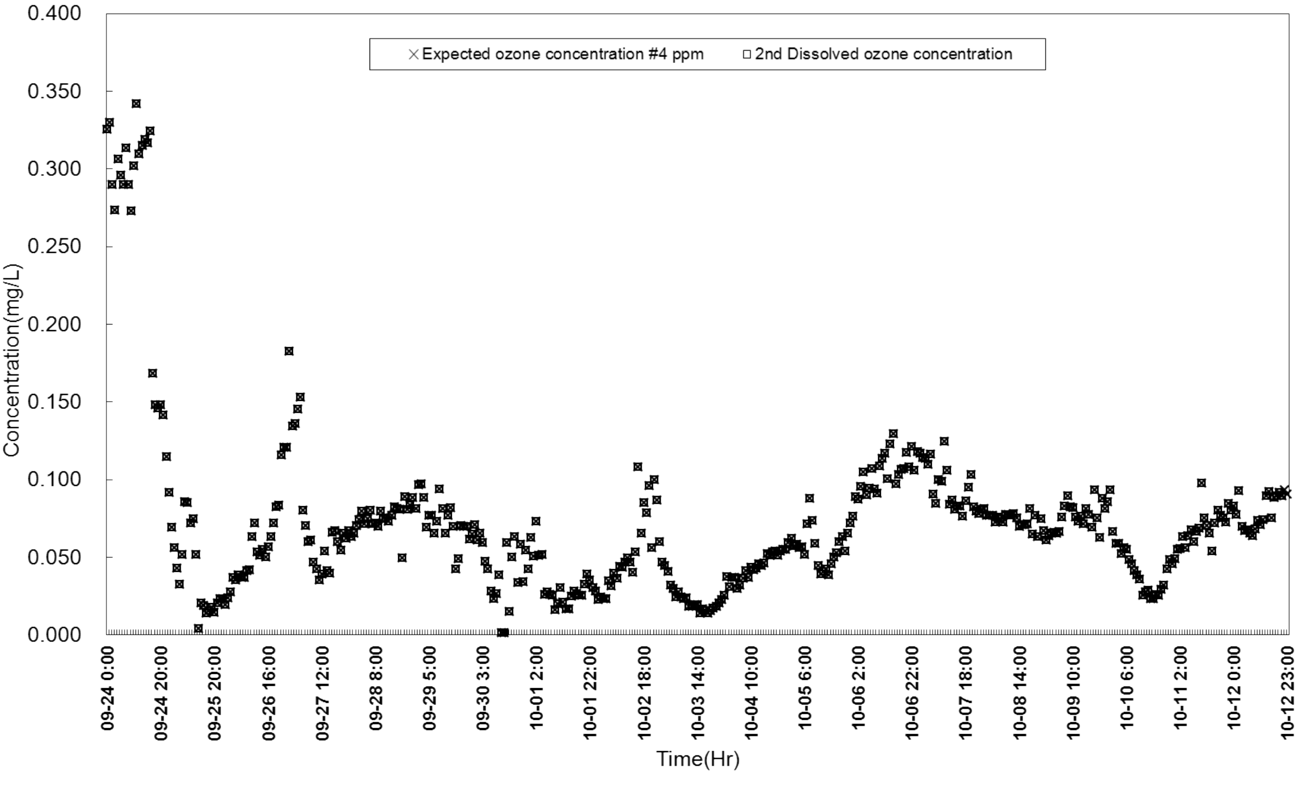

Fig. 11. KAWTP's second dissolved ozone concentration and estimated value (September 24–October 12).

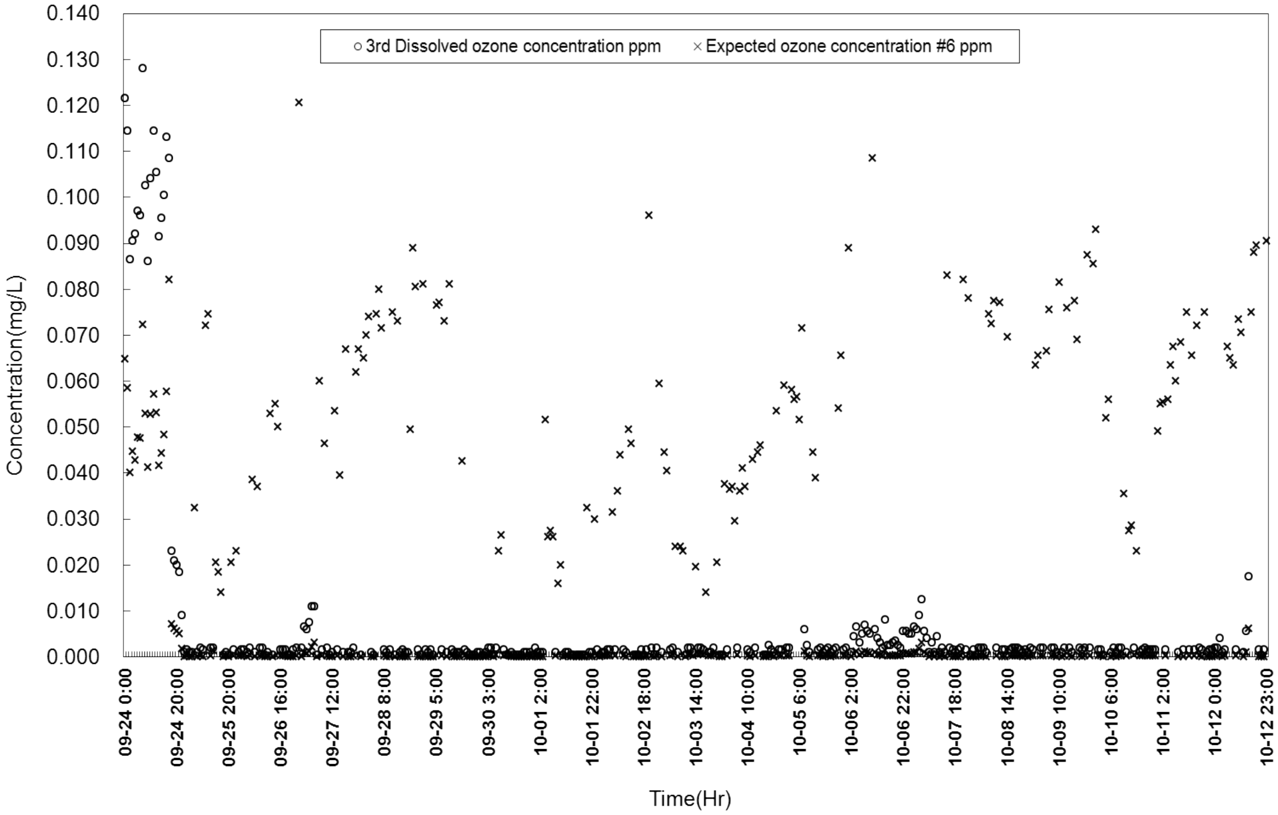

Fig. 12. KAWTP's third dissolved ozone concentration and estimated value (September 24–October 12).

that the ozone residual control at all the positions in the ozone reactor tank is achieved as desired.

3.7. Results from operation of modified extended CSTR method

Continuous operation of modified extended CSRT method in KAWTP was not always possible because the extended CSTR method is not still officially accepted for a formal CT credit in Korea. When the process is operated according to the *Cryptosporidium* log inactivation standard using the modified extended CSTR method, however, it was shown the ozone residual of the effluent could be constantly kept below 0.1 mg/L, which is the interim criteria in the WTP. Therefore, KAWTP temporarily operated the modified-extended-CSRT method to evaluate the adaptability of the method, and the results are shown in Fig. 13. It was shown that the log inactivation is adequately fulfilled and varied according to the change of the operating conditions. The ozone residual of the effluent during the initial operation period (9.25–9.30) are 0.002 mg/L (average) and 0.011 mg/L (maximum), indicating that it is operated below the criteria of 0.1 mg/L, and that it is expected to be able to achieve both goals of acquiring a CT credit and maintaining the ozone residual of the effluent below 0.1 mg/L.

3.8 Simulation results of the ozone dose control by two methods with different water quality and flow rate

Simulated are shown in Table 2. As shown in the table, the simulated results show that the final ozone residual is lower than that in the ozone control based on K_c in most simulated cases where *Cryptosporidium* log inactivation was 1. It was only when the maximum current of 350,000 m^3/d (only in blueprint) flowed in that the final ozone residual was simulated to exceed 0.1 mg/L. The ozone dose was also shown to be lower in the *Cryptosporidium* log inactivation mode. When the inflow rate increased to approach the maximum capacity, the calculated ozone dose in the *Cryptosporidium* log inactivation mode and K_c based ozone control mode became similar or to greater than. Therefore, it is adjudged that applying the modified extended CSTR method would be more economical, but since the process is not accepted officially, the current best choice would be to use the K_c based ozone control method where the final ozone residual was maintained below 0.1 mg/L.

4. Conclusion

According to the operation results of the automatic ozone dose control system based on K_c calculation, ad-

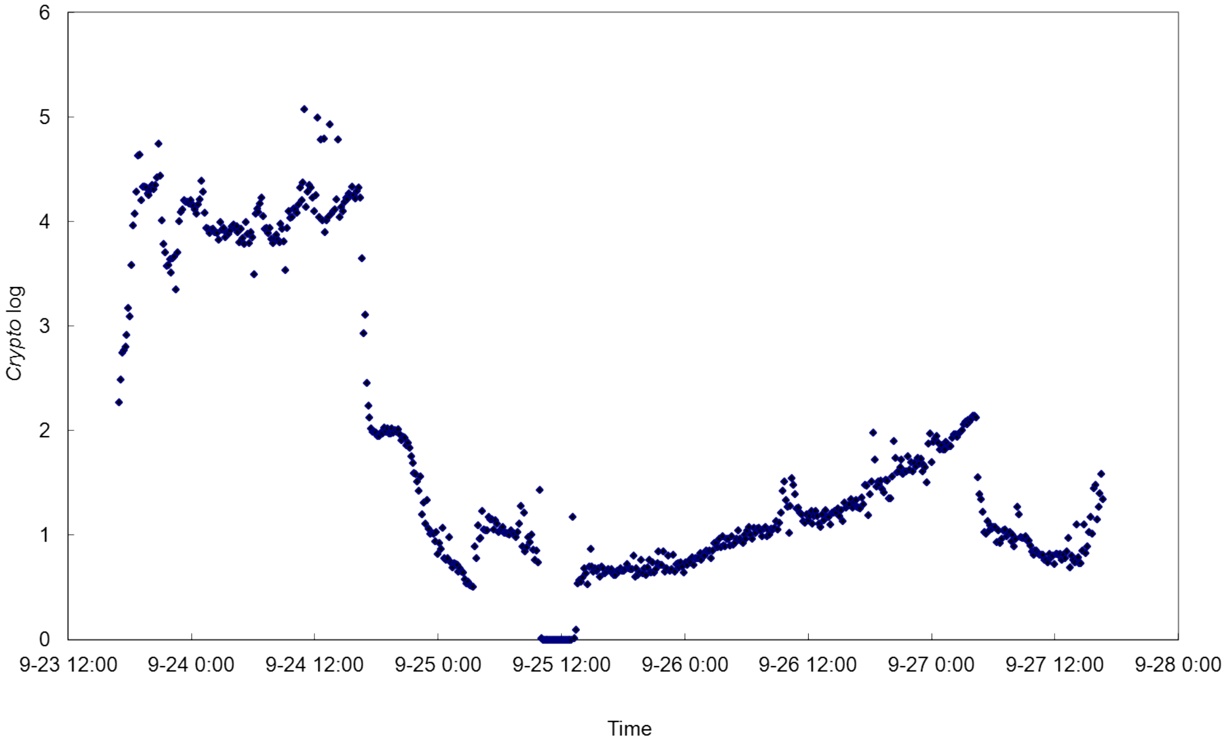

Fig. 13a. Variation of *Cryptosporidium* log inactivation with changed goal (from 4 to 1).

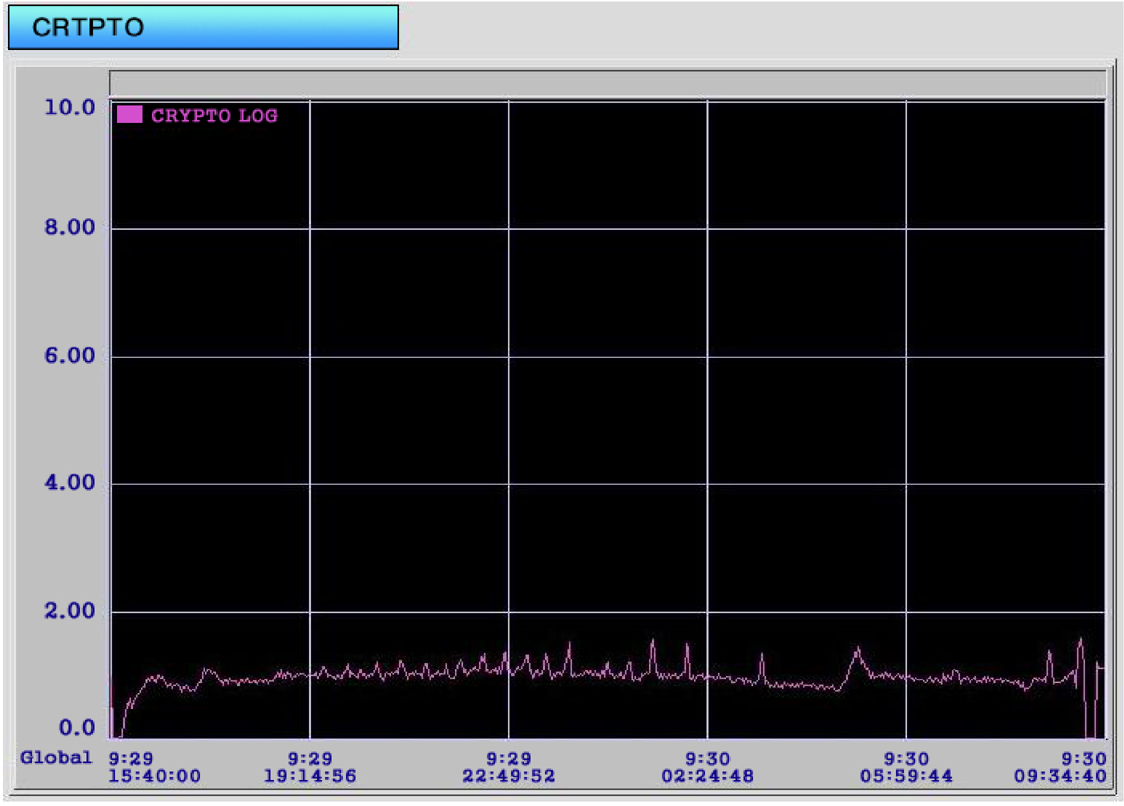

Fig. 13b. Variation of *Cryptosporidium* log inactivation with constant goal of 1.

Table 2
Simulated results of K_c based ozone dose control method and *Cryptosporidium* log inactivation method

Category	Flow rate (m^3/d)	K_c based ozone dose control method (0.1 mg/L)	*Cryptosporidium* log inactivation method		Conditions
		Calculated ozone dose (mg/L)	Calculated ozone dose (mg/L)	Calculated the final ozone residual (mg/L)	
Case 1.1	144,000	2.5	0.82	0.011	ID: 0.344 C_0: 0.856 K_c: –0.111
Case 1.2	210,000	1.53	0.86	0.043	
Case 1.3	298,000	0.93	0.93	0.1	
Case 1.4	350,000	0.80	0.97	0.138	
Case 2.1	84,450	2.5	0.71	0.004	ID: 0.0141 C_0: 0.832 K_c: –0.0894
Case 2.2	210,000	0.75	0.34	0.052	
Case 2.3	285,000	0.46	0.45	0.099	
Case 2.4	350,000	0.353	0.50	0.143	

equate ozone dose calculation along with the various water quality and inflow rate was performed successfully, and the ozone residual of the effluent was also maintained below the lowest set value during operation. Moreover, the process was adequately run to maintain the target log inactivation the *Cryptosporidium.* The ozone process's three major parameters calculated during the operation are as follows:

During the operation period, the calculated pseudo first-order decay rate constant (K_c) K_{c1} values were –0.105 min^{-1} (average), –0.034 min^{-1} (maximum), –0.282 min^{-1} (minimum), and the K_{c2} values were –0.111 min^{-1} (average), –0.013 min^{-1} (maximum), and –0.262 min^{-1} (minimum).

During the operation period, the calculated ID values were 0.262 mg/L (average), 0.666 mg/L (maximum), and 0.0045 mg/L (minimum).

During the operation period, the ozone doses were 0.781 mg/L (average), 1.269 mg/L (maximum), and 0.468 mg/L (minimum).

Moreover, the ozone residual within 40% retention time of the ozone reactor tank was 100% predictable. The final ozone residual was so low that there were some deviations from the estimated value, which seems inevitable considering the valid measurement range of the instruments. Most of the simulated results and real ozone residual, however, were shown to be below the operation criteria of 0.1 mg/L, confirming that the Kc based ozone dose control method was being adequately run. It was also shown that during the operation, *Cryptosporidium* log inactivation mode using the modified extended CSTR method, the ozone process was being successfully controlled to maintain the set log value. When the calculated operation of the ozone process according to the inflow rate and water quality was estimated, *Cryptosporidium* log inactivation based ozone control mode and K_c based ozone control mode produced different results of the final ozone residual. An economic and stable ozone process could be selected between the two modes in full scale plant in the future. Also, calculating the optimal ozone dose that could completely oxidize ozone-consuming matters and leave minimum residual, could be economical due to excessive ozone dose saving, and the biological and physical stability of GAC granule in GAC process. It is also expected to minimize the release of harmful ozone gas to the atmosphere and to thus help improve the workplace environment.

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