1. Introduction
The advanced water purification treatment in the Bureau of Waterworks, Tokyo Metropolitan Government (hereafter “BWT”), uses a combination of ozone treatment and biological activated carbon treatment, which is adopted mainly for treatment of organic substances contained in raw water such as ammonium nitrogen, musty substances, trihalomethane (THM) precursor, etc. Ozonation is a process of dissolving organic substances and is largely related to the efficiency of biological activated carbon treatment that follows. Ozonation, however, has a problem of producing carcinogenic bromic acid, making appropriate ozone injection control indispensable.

The ozone injection control method includes control of dissolved ozone level (concentration), exhaust ozone level control, ozone generation control or the combination of these controls. Misato Water Purification Plant mainly uses the dissolved ozone level control method that allows comparatively steady control. The dissolved ozone level control is an independent feedback control system where the dissolved ozone level in ozonated water is controlled to a certain target value. Because of the unstable control due to variation in water quality, the target dissolved ozone level in the ozonated water gets widely extricated, causing problems such as deterioration of organic substance dissolution efficiency, increase of bromate production, etc.

One of the methods to solve such problems is stabilization of control through the combination of feed-back control and feed-forward control. In the case of BWT, however, since feed-forward control is not yet applied, efforts have been made to develop a new control method, and a new feasible one has been found as reported below.

2. Estimation of ozone dosage
Estimation of ozone dosage is indispensable to carry out feed-forward control. Considering that the ozone dosage is determined by the quality of water to be treated unless the treatment condition changes, the ozone dosage estimate formula was deduced from the multiple regression analysis using water quality index.

2-1. Extraction of water quality index
The water quality index for estimation of ozone dosage was extracted from the items generally considered related to ozone reaction and measured continuously in advanced purification treatment system using automatic water quality measuring instruments. The items measured continuously in the advanced purification system in Misato Water Purification Plant are: water temperature, turbidity, pH, ammonium nitrogen, dissolved oxygen, UV260, TOC and fluorescence intensity.

The items extracted were: water temperature closely related to ozone solubility, pH related to autolytic rate, and turbidity and organic substances as the matters consuming ozone. Among the 3 items of organic substances, namely UV260, TOC and fluorescence intensity, the fluorescence intensity with high sensitivity to ozonation (according to the result of investigation carried out in
the last fiscal year\textsuperscript{(1)} was chosen as the organic substance index.

The multiple regression analysis was carried out on the 4 items of water quality index and the ozone dosage using 1-hour data (n = 3292) between June 28, 2004 and September 24, 2004, and between October 15, 2004 and December 3, 2004, and the regression equation (1) with coefficient of determination 0.8927 was obtained.

\[
\text{Ozone dosage} = 0.055 \ \text{(fluorescence intensity)} + 0.043 \ \text{(water temperature)} + 0.22 \ \text{(turbidity)} + 0.64 \ \text{(pH)} - 5.6 \quad \cdots \quad (1)
\]

(Units - Ozone dosage: mg/L, fluorescence intensity: Absolute intensity, water temperature: °C)

As shown in Fig. 1, the difference between ozone dosage calculated from equation (1) and actual dosage is less than ±0.2 mg/L, indicating that the extracted water quality index can be used for estimation of ozone dosage.

2-2 Derivation of ozone dosage estimate equation

Since ozone dosage is largely affected by the ozone solubility, ozone dosage was newly estimated from ozone consumption using equation (2).

\[
\text{Ozone consumption} = \text{Ozone dosage} \times \text{dissolution efficiency} - \text{dissolved ozone level} \quad \cdots \quad (2)
\]

(Units - Ozone consumption: mg/L, dissolved ozone level: mg/L)

Ozone consumption is generally calculated from the quantity of ozone injected, the quantity of ozone exhausted, and the dissolved ozone level. However, since the use of exhaust ozone makes the calculation complicated and since the use of estimate equation is restricted to Misato Water Purification Plant, equation (2) has been adopted, with the rate of injected ozone dissolving in water regarded as ozone dissolution efficiency (hereafter "dissolution efficiency").

In Misato Water Purification Plant slight prechlorination is carried out in summer even in the
advanced treatment system for controlling bromate production and as a countermeasure against proliferation of algae in settling tank. From the results of investigation so far made (Fig. 2) prechlorination obviously causes the ozone dosage to decrease, and therefore estimate equations as per chlorine dosage have been deduced.

In order to clearly indicate the estimate accuracy, manual analysis with higher accuracy than automatic water quality measuring instrument was adopted for the used data. Although dissolution efficiency is considered to differ according to the structure of the ozonation facility and the water temperature, the dissolution efficiency of 0.85 was adopted for deducing the estimate equation on the basis of the result of investigation made in Kanamachi Water Purification Plant.

Estimate equations as per chlorine dosage are given in equations (3) ~ (5) and the difference between estimated and measured values is shown in Fig. 3.

Estimate equations as per chlorine dosage

- **<Chlorine dosage: 0.0 mg/L, coefficient of determination: 0.9409, n = 16>**
  \[
  \text{Ozone consumption} = 0.038 \text{ (fluorescence intensity)} + 0.025 \text{ (water temperature)} + 0.31 \text{ (turbidity)} + 0.58 \text{ (pH)} - 4.6 \quad \cdots \ (3)
  \]

- **<Chlorine dosage: 0.5 mg/L, coefficient of determination: 0.9456, n = 24>**
  \[
  \text{Ozone consumption} = 0.055 \text{ (fluorescence intensity)} + 0.029 \text{ (water temperature)} + 0.14 \text{ (turbidity)} + 0.34 \text{ (pH)} - 3.3 \quad \cdots \ (4)
  \]

- **<Chlorine dosage: 1.0 mg/L, coefficient of determination: 0.9496, n = 29>**
  \[
  \text{Ozone consumption} = 0.045 \text{ (fluorescence intensity)} + 0.029 \text{ (water temperature)} + 0.33 \text{ (turbidity)} + 0.45 \text{ (pH)} - 4.0 \quad \cdots \ (5)
  \]

As the difference between estimated value and actually measured values is less than 0.1 mg/L in most cases in Fig. 3, irrespective of chlorine dosage, it has been proved that the estimate accuracy is fairly high.

The coefficient of determination (0.92660) showed little change even when all data were used without taking chlorine dosage into consideration, but the difference between estimated value and measured value exceeded ±0.1 mg/L with a high probability of 4% ~ 13%.

3. Calculation of dissolution efficiency due to simulation

In deducing the estimate equations (3) ~ (5), the dissolution efficiency was obtained on the basis
of the investigation results in Kanamachi Water Purification Plant. However, the injection method in Misato Water Purification Plant and Kanamachi Water Purification Plant slightly differs, calling for attention in determining the dissolution efficiency in Misato Water Purification Plant. Further, since the dissolution efficiency is largely affected by water temperature, temperature-wise determination of the dissolution efficiency ensures improved estimation accuracy. Hence, the estimate equations were simulated by changing dissolution efficiency to examine its relation with the water temperature. The data used for simulation are the continuously measured values for 2 days using automatic water quality measuring instruments when the effect of chlorine dosage is nil within a time period during which the chlorine dosage remains continuously at a constant level. Further, the dissolution efficiency was changed by 0.05 starting with 0.85.

Fig. 4 shows the relation between average water temperature and dissolution efficiency obtained from the simulation results. As is clear from the figure, the ozone dissolution efficiency declines as the water temperature rises, indicating the relation similar to the solubility of ozone in water. The simulation results under various conditions are shown in Fig. 5.

We could not estimate the dissolution efficiency in our investigation this time because of the unavailability of the data (for dissolution efficiency) at low water temperature below 15°C and high water temperature above 31°C. However, the dissolution efficiency of 0.95 at water temperature below 15°C, considered normal for countercurrent contact method, was chosen as the right figure.

![Fig. 4: Average water temperature vs. dissolution efficiency](image-url)
4. Verification of estimate equation

The estimate equation was put to verification by using the data of fiscal year 2005 in order to verify the availability of the estimate equation. Since the spring data were not used in the estimate equation of fiscal year 2004, the data of April and June of fiscal year 2005 were added before derivation of the estimate equation, and this equation was used for verification. The verification term was between July and early in August of 2005. The value calculated by using the
estimate equation and the actual dosage are given in Fig. 6. The result shows the calculated value at lower level, but the difference is confined merely to 0.1 mg/L. Further, since the value corresponds well to the variation, the estimate equation was considered applicable. The estimate equation can be further improved for higher accuracy in the future by adding data.

5. Development of feed-forward and feed-back control method

Since the ozone dosage could be estimated with high accuracy by using the newly defined dissolution efficiency, study was made on the feed-forward and feed-back control method using the estimate equation.

The ozone dosage can be obtained by equation (6), the changed form of equation (2).

Ozone dosage = Ozone consumption + management target (goal) for dissolved ozone/Dissolution efficiency (6)

The ozone consumption can be obtained by equations (3) ~ (5), and the dissolution efficiency by water temperature in Fig. 5. The management target for dissolved ozone level in Misato Water Purification Plant at present is 0.05 mg/L for ozonated water.

However, because of the estimated error in calculated value, the actual dissolved ozone level (concentration) sometimes fails to conform to the management target, calling for dosage correction.

Corrected ozone dosage can be obtained from equation (7).

Corrected ozone dosage = Calculated ozone consumption + (Dissolved ozone management target - Dissolved ozone level) + Dissolved ozone management target / Dissolution efficiency --- (7)

The feed-forward and feed-back control method based on equation (7) was developed. The flow chart of the newly developed method is shown in Fig. 7. In the flow chart the chlorine dosage data of 2 hours before is adopted since the reaching (concentration) time from prechlorination to advanced water treatment pumping well is approximately 2 hours.
6. Conclusion
Development carried out for feed-forward and feed-back control of ozone injection for optimization of ozonation has made the following points clear.
① It is possible to estimate the ozone dosage using the water quality indexes such as fluorescence intensity, water temperature, turbidity and pH.
② Highly accurate estimate equation was obtained from the ozone dosage estimate equations as per prechlorination dosage obtained from water quality indexes.
③ The dissolution efficiency of ozonation facility in Misato Water Purification Plant is 0.95～0.70 at water temperature 15℃～30℃, with the efficiency getting decreased as the water temperature rises.
④ Verification of the estimate equation obtained from the 2004 data using the 2005 data showed that the estimate equation was applicable.
⑤ Based on the aforesaid results, the feed-forward and feed-back control method was developed. We are determined to carry out verification of the newly developed control method and to improve the accuracy of estimate equation in order to supply safer and cleaner tap water.
Note: The newly developed control method has been acknowledged as a “service invention” by the Bureau’s Invention Examination Committee, and an application has been filed for the patent.