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ANALYSIS AND SIMULATION TECHNIQUES FOR WATER QUALITY IN WATER DISTRIBUTION NETWORKS

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1. FOREWORD

The importance of water quality management due to worsening of the environment surrounding water source quality, generation of red water in supply and distribution pipes, increase of trihalogen methane, etc. is a long-standing cry. However, it is no exaggeration to say that system technology related to water quality is behind system technology related to water usage systems and other water transportation. For this reason, the constitution of water quality change accompanying chemical reaction is complicated and is easily affected by various factors. Further, as typified by the word "delicious water", it is difficult to measure and numerate taste, oder, and minute substances.

Under these circumstances, Fuji Electric has practicalized an ozonizer for advanced treatment, applied fuzzy logic to chemical injection control in filtration plants, developed a robot for water quality analysis, etc.

Regarding the water quality problem in water distribution pipelines, techniques for analyzing residual chlorine concentration are being established. However, up to now, static analysis (constant flow) has been the mainstream and dynamic analysis is necessary for use in control positively The method of analyzing the variation with time of the residual chlorine concentration distribution considering the daily demand variations and its application technology are introduced.

2. ANALYSIS METHOD

2.1 Purpose of analysis

A residual chlorine concentration of 0.1 mg/l or more must be guaranteed at the terminal tap. Conversely, since there are no restrictions on the upper limit, the general tendency is to inject excessive chlorine. However, because of the increase of trihalogen methane and the demand for "delicious water", injection of the minimum necessary amount of chlorine is demanded. Whereas the water flow and water pressure in the pipeline move as a wave motion at a speed of about 1000m/s, since a substance itself is moved, the time wasted up to the terminal is very large. Therefore, in the case of water pressure control, the water pressure can be feedback controlled by measuring the terminal water pressure. However, this cannot be done in the case of water quality. (Whereas the main period of variation is one day. The wasted time is a equal to, or a fraction of, this.) Therefore, for optimum injection of chlorine, the characteristics of the reduction of residual chlorine in the water distribution pipeline must be clarified. Because, the retention time in the pipeline, of course, has a large affect on reduction of the residual chlorine, and this time is closely related to flow, dynamic residual chlorine concentration distribution analysis considering the daily demand variation is performed.

2.2 Basic equations

(1) Residual chlorine reduction characteristic

The residual chlorine reduction characteristic was assumed to conform to the following primary reaction expression by the experiments of Nakanishi:

$$C = C_o \cdot e^{-kt} \qquad (1)$$

Where, C is the residual chlorine concentration after elapsed "t" hours (residual chlorine concentration is called simply concentration hereinafter), C_o is the initial concentration, and k is the concentration reduction speed coefficient that related to the water quality, water temperature, flow velocity, pipe material, contact area with the pipe, etc.

Goto introduced the following experimental expression by multiple regression analysis of the measured result:

$$\mathrm{In}k = k_D \cdot D + k_T \cdot T + k_o \qquad (2)$$

Where, D is the pipe diameter, T is the water temperature, and k_D, k_T, and k_O are partial regression coefficients and are found for the three kinds of pipe as shown in *Table 1*.

(2) Calculation of concentration in pipe

The relation of the upstream concentration C_A and downstream concentration C_B [*Fig. 1* (a)] of the pipeline of a certain zone becomes as shown below by means of Eq. (1).

$$C_B(t) = R \cdot C_A\,(t - t_s) \qquad (3)$$

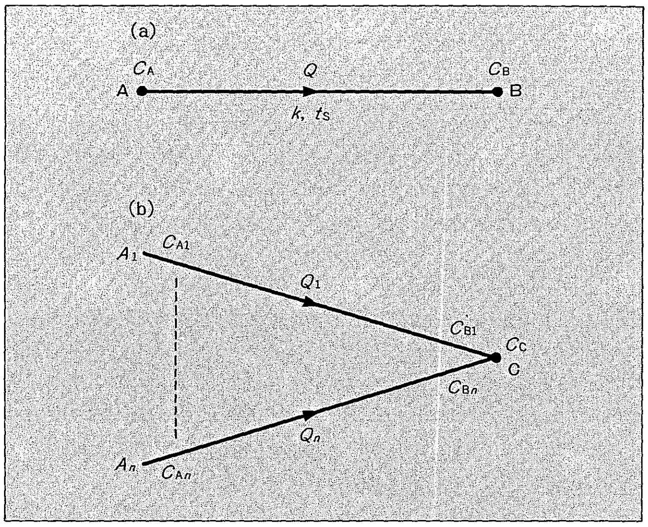
$$R = e^{-k \cdot ts} \qquad (4)$$

Table 1 Partial regression coefficient by pipe material

Types of pipe	k_D	k_T	k_O
FCD	–5.1349	0.0842	–5.7582
EPX	–5.0419	0.0918	–5.7775
FC	–6.2598	0.0329	–1.6168

FCD: Mortar lined ductile cast iron pipe
EPX: Epoxy resin lined cast iron pipe
FC: Unlined cast iron pipe

Fig. 1 Residual chlorine concentration at base pipeline and nodes



Where, t is the time and t_s and R are the retention time and concentration reduction rate of this zone, respectively. t_s is related to zone length L and flow Q as shown below.

$$\int_{t-t_s}^{t} Q(\tau)d\tau = \pi D^2 \cdot L/4 \quad \ldots\ldots\ldots\ldots (5)$$

Where, if $Q(\tau) = Q_o$ (constant), from E_q. (5),

$$t_s = \pi D^2 \cdot L/4Q_o \quad \ldots\ldots\ldots\ldots (6)$$

(3) Calculation of concentration at convergence point

At points where multiple pipes converge, the concentration becomes as follows when mixed completely after convergence [*Fig. 1* (b)] :

$$C_c(t) = \sum_{i=1}^{n}\{Q_i \cdot C_{Bi}(t)\} / \sum_{i=1}^{n} Q_i \quad \ldots\ldots\ldots\ldots (7)$$

Where, n is the number of pipes flowing in to point B and Q_i and C_{Bi} are the flow and downstream side concentration of pipe i flowing to point C, respectively.

2.3 Static water quality distribution

As shown in the preceding section, to calculate the water quality distribution, the flow distribution and flow direction of each pipeline are necessary. Therefore, first, the flow of each demand end is given and the flow distribution of each pipeline is calculated by pipe network analysis. When the flow is assumed to be constant from the standpoint of time, if the concentration of the injection point is given, from Eqs. (3) to (7) the concentration at each consumer end is tentatively set without regard to time. However, calculations must be made sequentially from upstream side to downstream side in the direction of flow.

Against this, a water quality distribution solution which satisfies the previously mentioned relationship is obtained by means of the following repetitive calculation without being conscious of the calculation order. Since flow direction changes can be dealt with and troublesome pipe path search is omitted with this method, fast calculation is possible.

(1) The retention time t_s and concentration reduction rate R of each pipeline is calculated from the flow distribution obtained by pipe network analysis. The entrance pipe and its upstream side nodes are stored for each node (consumer end, branches and convergence points) from the flow direction.
(2) The upstream side concentration of each pipeline is provided zero. The injection concentration of only the injection point is given.
(3) The upstream side concentration of each pipeline is multiplied by the concentration reduction rate and the downstream side concentration is calculated.
(4) The exit pipe upstream side concentration is calculated from the concentration and flow of the entrance pipe downstream side for each node.
(5) Steps (3) and (4) are repeated and calculation is terminated when the difference with the concentration of the preceding time becomes smaller than the specified value.

The number of times calculation is maximum and becomes the maximum value of the depth of the pipe path (number of pipelines from the injection point to the end).

2.4 Dynamic water quality distribution (time variation of water quality)

When the time variation of flow is considered, the retention time of each pipeline varies with time and only the flow at a certain point is determined. Since ts which satisfied Eq. (5) is not obtained analytically, it is found by numerical calculation.

The calculation procedure is described below.

(1) First, calculation is performed with the initial state distribution as the steady state by the static water quality distribution calculation method described previously.

The following calculation is performed at each calculation time interval.

(2) Pipe network analysis is performed under the conditions (injection point concentration, demand end flow, etc.) of the pertinent time and the flow distribution of each pipeline is calculated.
(3) The retention time, concentration reduction rate, and flow direction are found by the method described previously.
(4) The concentration before the retention time of the upstream side of each pipeline is found by interpolation from the concentration of the calculation points before

and after that time. For time before the calculation start time is made the initial concentration.

(5) The pipeline downstream side concentration and node concentration are calculated the same as (3) and (4) of the preceding section.

(6) For pipelines with a retention time shorter than the calculation time interval, the concentration at the calculation time is used in interpolation. Thereupon, for these pipelines, steps (4) and (5) are repeated and calculation is terminated when the difference from the concentration of the preceding time becomes smaller than the specified value.

2.5 Simple calculation of dynamic water quality distribution

For the method described in the preceding section, pipe network calculation must be performed at each calculation interval. Against the water quality distribution calculation from step (3) of the preceding item, the calculation contents of pipe network analysis are complex and calculation takes time.

On the other hand, there are many cases where all the demand ends are considered to vary by the same pattern (ratio of demand amount of each time and daily amount of each demand end). Under such conditions, for a single injection point, the flow of each pipeline is proportional to the demand amount. (The loss head is assumed to be proportional to the power of the flow.) This also applies to multiple injection points, if it is assumed that the ratio of the inflow of each injection point does not change with time.

If only pipe network analysis is performed in the initial state, the flow of each pipeline at calculation point is obtained by multiplying the pipeline flow in the initial state by the demand amount time ratio (ratio of demand amount at the time of calculation to the initial demand amount). Water quality variation is calculated by the same technique as described in the preceding section, except that pipe network calculation is not performed at each calculation time.

3. APPLICATION TECHNOLOGY

3.1 Analysis program

The analysis method described in the preceding section has been programmed so that it can be applied to general purpose pipe networks. This program runs on the FACOM VP series, M series, A series, and other computers.

Pipe network analysis can also be applied to large pipe network at high speed by using the McIlroy · Aoki method, which is a flow method.

The reduction speed coefficient can be input by the following methods:

(1) Specification of coefficient for each pipeline.

(2) Calculation in program as diameter, water temperature, and material function [Eq. (2)].

When calculating the dynamic water quality distribution, the time variation of the injection point concentration and the demand amount variation pattern are given.

The following are obtained as output:

(1) Pipe network analysis output
 (a) Flow and loss head of each pipeline
 (b) Head and remain head of each node
 (c) Pipe network flow direction diagram, pressure contour line diagram, pipe network analysis diagram

(2) Static water quality distribution
 (a) Retention time, concentration reduction rate, and upstream and downstream sides concentration of each pipeline
 (b) Water quality contour diagram

(3) Dynamic water quality distribution
 (a) Concentration and demand amount variation graph of arbitrary node by specification.
 (b) Nodes and time below standard concentration

3.2 Application to pipe network planning and design

Pipe network analysis is indispensable in pipe network expansion, updating, blocking, and other planning and design. Usually, the plan time maximum supply amount and (dairy maximum supply amount when it is planned+ amount of water for fire fighting) at a disaster are calculated and checking whether the pressure at the terminal is sufficient is the main purpose.

From the standpoint of residual chlorine concentration, the period of small amount with long retention time is important. Since small diameter pipes have little effect on pressure, they are omitted from pipe network calculation for simplification. Small diameter pipes with a high velocity have a relatively large effect on water quality analysis. In pipe network analysis and water quality analysis for the same pipe network system, demand amount and pipe network modeling msut be considered with a different standard.

Concerning the demand amount, when static water quality distribution calculation is applied at planning and design, usage of average supply amount in a day will be suitable. The hourly minimum demand is not used, because the retention time is not determined only the flow at that time, but the history of flow until at that time and the flow is averaged with time. Because the water temperature has a large affect on the reduction speed coefficient and reduction becomes easier as the water temperature becomes higher, the high water temperature period should be considered the subject for design. If applied by taking these points into account, static water quality analysis will be sufficient at planning and design.

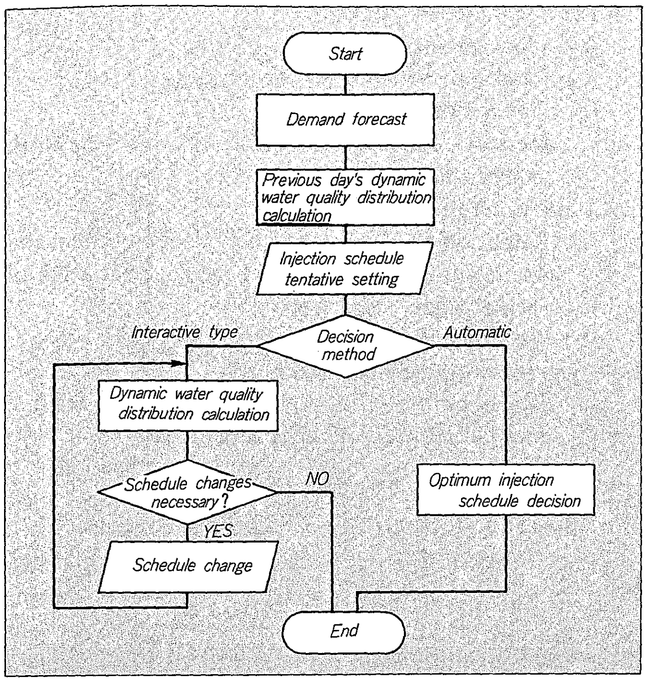
3.3 Application to chlorine injection control

When applied to control of chlorine injection, analysis of dynamic water quality distribution is beneficial. It is performed as follows:

(1) The water distribution amount per hour of the next 24 hours is forecast by demand forecasting.

(2) The injection point (water distribution reservoir or clean water reservoir) set concentration schedule is tentatively decided. (Constant or previous day's pat-

Fig. 2 Dosage control schedule decision flowchart



tern, etc.)

(3) Dynamic water quality distribution is calculated based on the actual water distribution amount and injection concentration from the preceding 24 hours to the current time. (Because a history is necessary)

(4) The dynamic water quality distribution for the next 24 hours is simulated based on the forecast demand amount and injection concentration schedule. However, simulation is performed with the calculated result of (3) as the initial condition.

(5) If the injection concentration schedule must be changed based on the simulated result, it is changed and the simulation of (4) is repeated. That is repeated over and over and the injection concentration schedule is decided so that the water quality distribution which should be satisfied is obtained.

The trial and error process (interactive) of (5) gives (automatically decides) an injected chlorine concentration schedule which maintains the chlorine concentration at the objective node nearly at the desired value. Now suppose that the deviation from the desired concentration at time intervals of "Δt_1" at the desired node obtained from the simulation (4) equals xi^0 ($i = 1\sim n$), and the injection schedule of "Δt_2" intervals is yj^0 ($j=1\sim m$). In this case, $n = 24/\Delta t_1$, $m = 24/\Delta t_2$, and the deviation $X_i = x_i - \bar{x}_i$ are employed. In order to obtain the sensitivity of the deviation "X_i" from the desired concentration ($\bar{x}_i$) at the moment of "i" with the chlorine injection quantity of "Y_j", "Y_j" is incremented by "ΔY" to calculate the dynamic water quality distribution. Thus variation "ΔX_{ij}" of "X_i" is obtained i.e. $\partial X_i / \partial Y_i = \Delta X_{ij} / \Delta Y$ is obtained. From this, "x_i" can be expressed as follows:

$$\begin{bmatrix} \Delta X_1 \\ \vdots \\ \Delta X_n \end{bmatrix} = \frac{1}{\Delta Y} \begin{bmatrix} \Delta X_{11} & \cdots & \Delta X_{1m} \\ \vdots & & \\ \Delta X_{n1} & \cdots & \Delta X_{nm} \end{bmatrix} \cdot \begin{bmatrix} \Delta Y_1 \\ \\ \Delta Y_m \end{bmatrix} \quad \cdots\cdots (8)$$

Where $\Delta X_i = X_i - X_i^0$ ………………… (9)

$\Delta Y_j = Y_j - Y_j^0$ ………………… (10)

Furthermore, if an upper and lower injection limit is considered:

$$Y_L \leqq Y_j \leqq Y_M \quad \cdots\cdots (11)$$

where Y_L : lower limit of injection
Y_M : upper limit of injection

Since the chlorine concentration cannot be less than the desired value:

$$X_i \geqq 0 \quad \cdots\cdots (12)$$

Thus Y_j ($j = 1\sim$m) which minimize the following as a subject is obtained by linear programming:

$$J = \sum_{i=1}^{n} \cdot |X_i| = \sum_{i=1}^{n} X_i \quad \cdots\cdots (13)$$

These procedures are shown in flowchart form in *Fig. 2*.

3.4 Application to pollution diffusion analysis

The basic equations are not expressions related to residual chlorine concentration only, but also apply to water quality in general. Therefore, they can also be applied to the simulation of diffusion (spread of the pollution range, ultimate time, and concentration change) after red water generation and the generation of pollution by cross connection.

Table 2 Water quality analysis application technology

Purpose	Analysis item	Analysis method	Point, attention item
Pipe network planning and design New pipeline construction Pipeline modernization Pipe network blocking	Suitable diameter and route Suitability and range of blocking	Pipe network analysis (pressure, flow) Static water quality distribution	Pipe network analysis at maximum hourly supply amount Water quality distribution calculation at average hourly supply amount Pipe network modeling range
Chlorine injection control	Necessary minimum (optimum) injection time schedule	Dynamic water quality distribution (simple calculation)	High speed operation demanded because repeated calculation necessary.
Pipe network pollution diffusion Red water Cross connection	Effect range Ultimate time Valve operation Water interrupt area	Dynamic water quality distribution	Analyzed result display method Pollution generation mechanism is separated.

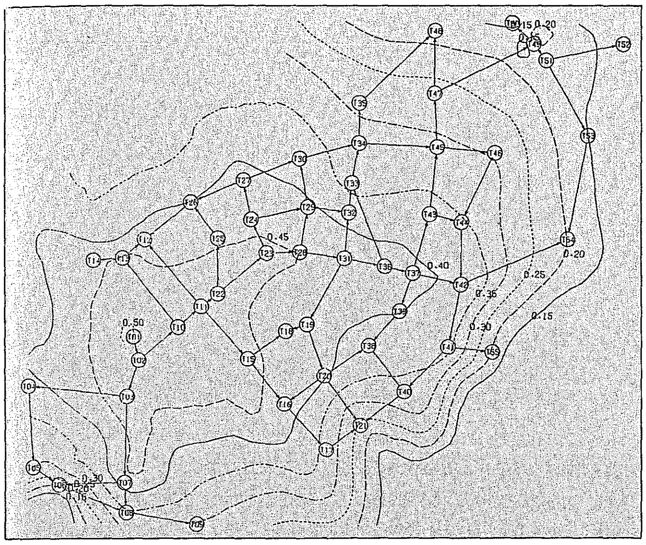


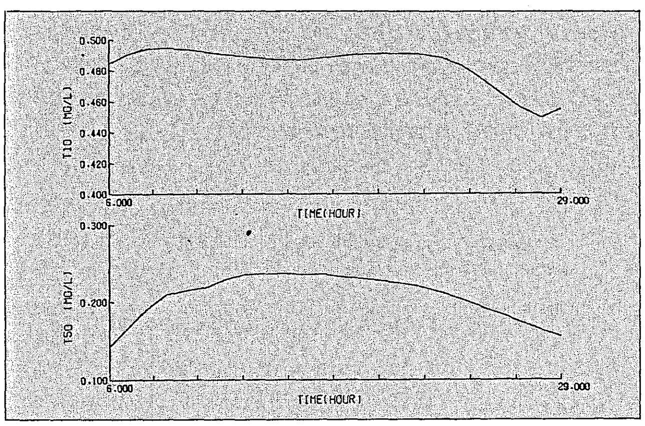
Fig. 3 Simulation example water quality contour lines

Fig. 4 Calculated result list output example (partial)

Calculated result CASE(TA01) 1/ 2

Pipeline name	Pipeline flow (m^3/h)	Retention time (hours)	Concentration reduction rate (%)	Upstream side node name	Upstream side chlorine concentration (mg/ℓ)	Downstream side node name	Downstream side chlorine concentration (mg/ℓ)
R01	105.693	0.196	98.640	T01	0.500	T02	0.493
R02	3.918	0.470	96.764	T02	0.493	T03	0.477
R03	1.679	3.071	80.658	T03	0.477	T04	0.385
R04	1.152	3.622	77.607	T04	0.385	T05	0.299
R05	0.287	5.553	67.794	T05	0.299	T06	0.203
R06	0.358	8.900	53.633	T07	0.419	T06	0.225
R07	0.571	4.129	74.897	T06	0.215	T08	0.161
R08	1.970	2.056	86.598	T08	0.343	T09	0.297
•							
•							
•							
•							
R71	7.919	1.785	88.253	T51	0.170	T53	0.150
R72	11.859	5.298	69.014	T47	0.271	T49	0.187
R73	0.963	3.917	76.021	T49	0.187	T50	0.142
R74	9.145	1.391	90.720	T49	0.187	T51	0.170
R75	1.226	23.067	19.895	T51	0.170	T52	0.034

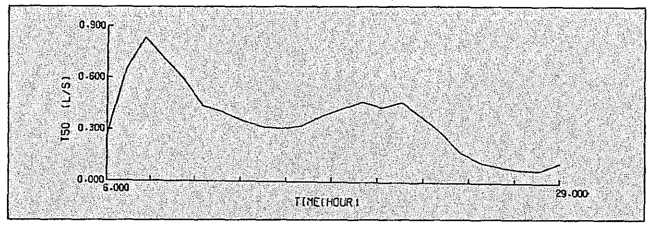
Fig. 5 Residual chlorine concentration time variation



4. SIMULATION EXAMPLE

An example of simulation performed on pipe network of a water distribution zone in a municipality is described. The injection point is the water distribution reservoir (Node T01 of *Fig. 3*.) The demand variation pattern of the demand ends was made the same (the demand amount is different for each node) and the dynamic water quality distribution was calculated for the next 24 hours with 6 A.M. as the starting point. The injection density was made fixed at 0.5mg/1.

Fig. 6 Node demand amount variation



The water quality contour lines in the initial state are shown together with the pipe network flow direction diagram in *Fig. 3*. That diagram expresses the condition of the deterioration for concentration along with the distance from injection point. However, since the contour lines are drawn approximately based on the concentration after convergence of each node, the concentration distribution in the pipeline between nodes is opposite the flow direction. (Because the concentration at each convergence point is noncontiguous) *Fig. 4* is the retention time, concentration reduction rate, upstream and downstream sides concentration, and other outputs (partial) of each pipeline.

Fig. 5 shows the variation of concentration with time at the nodes near (T10) and far (T50) from injection point. *Fig. 6* shows the variation of demand with time at node T50. The variation of concentration at the node near the injection point shows similarty to the variation of demand, oppositely the variation of concentration at the node far from the injection point shows difference because of large time delay.

5. CONCLUSION

The analysis method, application technology, and analysis examples centered about residual chlorine concentration were described as water distribution pipe network water quality analysis technology. Of these, the dynamic water quality analysis method and the new chlorine injection method using it were introduced. Future topics are described below.

(1) Direct measurement of the reduction speed coefficient which becomes the foundation of residual chlorine concentration variation is difficult for buried pipelines. Many examples were obtained by the efforts of those concerned with water treatment and the analysis technology described here is expected to have practical significance.
(2) The effectiveness of the dynamic water quality distribution method and injection control method in actual systems is verified.
(3) Combination with waterworks mapping system and systemization for displaying the water quality distribution on the piping map and displaying and specifying the affect range and the necessary water interruption area and users when pollution occurs is planned.

Since solution and application of these problems are planned and efforts are being made to help realize better water quality management, the guidance and support of those concerned with waterworks.