Advanced Water Treatment Technology for Waterworks and Sewerage Systems

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1. Introduction

One hundred years have elapsed since modern waterworks made their debut in Japan. Over this period, the saturation level of waterworks has exceeded 93% and Japan has literally entered an “era of high saturation.” However, due to the progress of industrial activities and concentration of the population in cities, various types of effluent flowing into the public water area has increased, and the offensive taste and odor of the tap water has become problematic. Further, it has become evident that various micro-organic pollutants and chlorinated materials exist in rivers, and the existence of trihalomethanes (THMs) in tap water has also become evident. Therefore, measures must be implemented in waterworks from a new viewpoint.

The recent deterioration of the water environment is becoming increasingly serious and the water environment is undergoing many various changes, regardless of artificial or spontaneous reasons such as micropollutants, such as pesticides and neutral detergents, eutrophication and the generation of pathogenic organisms.

In the future, the introduction of treatment and monitoring systems for pathogenic organisms, pesticides and micro-organic substances will be necessary, and especially, the regulation of disinfection byproducts is anticipated to become stricter.

It is expected that these treatment systems and measuring and monitoring system for micro-chemical substances will be developed in the future.

As for the trend of sewerage systems, the saturation level has exceeded 50% and their role is diversifying, as these systems are becoming an important infrastructure for daily life.

In the past, the role of sewerage systems was to collect and treat the wastewater discharged from the city and to remove the wastewater from our living area. Recently, however, treated sewage effluent has become an important water resource in the city.

Reflecting that status, disinfection of the treated sewage effluent requires a severity of methods. For example, when the treated sewage effluent is discharged into a clear stream where sweetfish are swimming and many sorts of aquatic life are living, chlorination is not suitable because of its residual property and influence upon the ecology. Disinfection using ozone or ultraviolet radiation is required because its non-residual property. Therefore, at the Hirose-river purification center in Sendai-city, ozone disinfection was employed. Further, when reusing treated water, the necessary disinfection level differs depending on the use, and disinfection technologies shall be investigated in consideration of water quality items that provide a person with comfort such as transparency.

In the past, the purification process utilized conventional treatments to guarantee tap water in conformance with tap water quality standards. Now, however, due to the state of water pollution in water resources, it is becoming necessary to maintain the water quality of raw water itself for tap water.

In this paper, the latest advanced water treatment technology for waterworks and sewerage will be introduced.

2. Advanced Water Treatment Technology for Waterworks and Sewerage

2.1 Current practices of advanced water treatment

2.1.1 Advanced water purification in waterworks

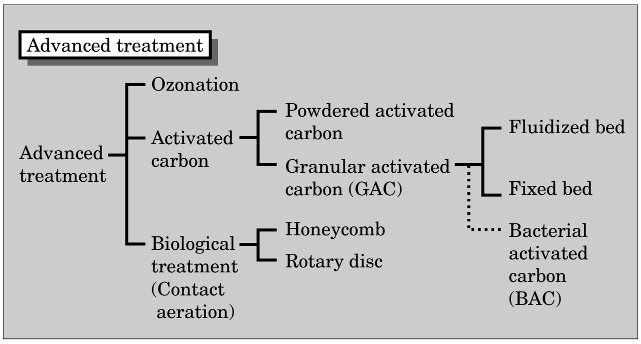
This treatment technology is used to treat odorous substances, trihalomethane forming precursors (THM-FP), trihalomethanes, color, ammonium nitrogen, anionic detergents, etc. which cannot be removed by conventional potable water treatments (coagulation-settling, slow filtration, rapid filtration and chlorination). This treatment technology is being applied in addition to the conventional treatment.

Advanced treatments are roughly classified into the following three treatments (Fig. 1), and when necessary, are applied in combination in addition to independent application. In particular, ozonation is effectively applied together with activated carbon in many cases.

(1) Effects of ozonation

Ozonation is a treatment that uses the much stronger oxidation of ozone instead of that of chlorine.

Fig.1 Advanced potable water treatment



The function and main usage effects of ozonation are as follows:

(a) Odor destruction : Odor and taste removal
(b) Removal of trihalomethanes and trihalomethane forming precursors
(c) Removal of color
(d) Conversion into smaller organic molecules : Improving adsorption of activated carbon
(e) Generation of biodegradable organic matter : Improving treatment of biological activated carbon (BAC)
(f) Removal of pesticides etc.
(g) Oxidation of iron and manganese
(h) Inactivation of virus

(2) Effects of biological treatment

Biological treatment is used to obtain the effect of treatment from a biochemical reaction created by organisms existing on a biofilm. There are two types of biological treatments, anaerobic and aerobic, but the aerobic treatment is normally used in the waterworks.

Biological treatment is effective on ammonium nitrogen, algae, moldy odors, anionic detergents, manganese, etc., and removes turbidity. Biological treatment reduces the color, $KMnO_4$ consumption, etc., but the potential for forming halogenated organic matter is hardly removed if the precursor is soluble.

(3) Effects of activated carbon

There are three advanced treatments: ozonation, activated carbon and biological treatment. However, if ozonation and activated carbon are used together, odors are almost perfectly removed, and the life of the activated carbon is prolonged because the burden has been shared between ozonation and activated carbon.

Among the activated carbon treatments, there is a so-called biological activated carbon (BAC) treatment. This treatment is a system in which microorganisms are attached on the surface of granular activated carbon, and both physical adsorption of the activated carbon and biological treatment by microorganisms are simultaneously performed. As mentioned above, in this case, the life of the activated carbon increases by three times or more compared to the normal case.

Table 1 Principal sewage advanced treatments and functions for the purpose of water reuse

Water quality item	Sand filtration	Activated carbon filtration	Ozone	Biofiltration
SS	◎	—	—	◎
Turbidity	◎	△	△	○
Color	—	○	◎	△
Odor	—	◎	◎	△
BOD	○	△	△	○
COD	△	○	△	△
Detergent	—	○	○	△
T-P	—	—	—	—
T-N	—	—	—	—
NH_3-N	—	—	—	○
E.-coli	△	—	◎	○
Dissolved inorganic substances	—	—	—	—

◎: Better ○: Effective △: Less —: None

Ozonation at the previous stage of the biological activated carbon treatment is effective in improving biological treatments. Ozonation and biological activated carbon treatment are generally applied in combination. The effects of combined ozonation and biological activated carbon treatment is as follows:

(a) The burden of the treatment can be shared.
(b) The combination has a wide-ranging treatment effect.
(c) By combining the biological activated carbon treatment at the next stage of the ozonation, byproducts formed by ozonation are removed.

Bio-refractory organic substances are decomposed into biodegradable substances in ozonation, and these are biologically removed in the biological activated carbon treatment tank.

2.1.2 Advanced water purification in sewerage

Advanced water purification is a general term for higher-level treatment technologies whose aim is reuse, environment protection, or the removal of substances that cannot be removed by conventional secondary treatments. The treatments are classified mainly into the removal of organic substances and removal of nutrients.

The following technology exists for advanced treatments in sewerage:

(1) Removal of organic substances

Coagulation and sedimentation, sand filtration, activated carbon filtration, ozonation, biological fixed bed, ultra-filtration and reverse osmosis

(2) Removal of nutrients

Coagulation and sedimentation, crystalization dephosphatation, break point chlorination, ion-exchange, activated sludge with coagulant, phospho-stripping, anaerbic-aerobic activated sludge, biological denitrification, oxidation ditch, batch-type activated sludge and reverse osmosis

From amongst these technologies, ozonation is especially excellent in removing colors and odors, disinfecting reused water, and in eradicating the ozone by self-decomposition so as not to influence the environment, differing from the residual of chlorination (Table 1).

2.2 Innovative advanced water treatment

2.2.1 Disinfection technology for Cryptosporidium parvum oocysts by ozone

In recent years, water-born group infection by Cryptosporidium parvum oocysts has become a severe social problem.

Cryptosporidium parvum is a parasitic protozoa, and only approximately $3\log_{10}$ of the infectious type of oocysts could be removed with conventional rapid filtration. Further, chlorination as a disinfectant in the waterworks hardly has any disinfecting effect. Moreover, the infective doses for human are so small that a 50% infective dose is 132 oocysts and a 1% infective dose is 2.4 oocysts. Therefore, this has become a very serious problem to guarantee water quality for sanitary tap water. To inactivate the Cryptosporidium parvum oocysts, treatment with ozone seems promising and the CT values of $2\log_{10}$ inactivation are 3.5 to 17mg · min/L estimated with the animal infection method and 12 to 16mg · min/L estimated with excystation. However, because of different experiment conditions and estimation methods, the CT values are greatly discrepant. Therefore, it is necessary to gather even more knowledge for defining the level of ozonation in water treatment.

Recent research on the ozonation disinfection of Cryptosporidium parvum oocysts conducted by the authors will be reported below.

(1) Influence of residual ozone

When testing under the conditions of pH 7, water temperature of 20°C and residual ozone of 0.05 to 0.5mg /L using excystation and the DAPI/PI staining test, the results showed that the influence of residual ozone was small and that the inactivation effect could be expressed with simple CT values. The inactivation CT values of 1 and $2\log_{10}$ were 6.3 to 7.6 and 10 to 12mg · min/L with excystation and 7.5 to 12 and 16 to 24mg · min/L with the DAPI/PI staining test. Further, the inactivation curve by ozone could be expressed with a series event model, and could be approximated with a two-hit model for estimation by excystation and with a one-hit model for estimation by the DAPI/PI staining test.

Using the mouse infection method, tests were conducted under the conditions of pH 7, water temperature of 20°C and residual ozone of 0.3 and 0.5mg /L. To estimate the infection, a Cryptosporidium parvum oocysts suspension after ozonation was centrifuged and washed 3 times, diluted step-by-step with 5 successive dilution series, and given to 5 scid mice (6 weeks of age) by oral-injection at every dilution step. After 4 weeks from the oral-injection, the oocysts in feces were examined, and an MPN (maximum probable number) was calculated. Defining ID (infective dose) as 1 MPN, and IF (infective factor) as the reciprocal of ID (infective dose), the relativity of the infective factor was estimated with IF/IF_0 (ID_0/ID). As the result, the $2\log_{10}$ inactivated CT values are approximately 3 and 6mg · min/L at residual ozone levels of 0.3 and 0.5mg/L respectively, and the lower the residual ozone is, the smaller the CT value. The $2\log_{10}$ inactivated CT values reported by Finch, et al. were 1.7 and 2.6mg · min/L at residual ozone levels of 0.25 and 0.5mg /L respectively, showing a similar tendency. From these results, inactivation by estimation of infection could possibility be dependent upon the residual ozone. The cause of the difference between our research and Finch's research must be investigated, but, judging both results comprehensively, the $2\log_{10}$ inactivated CT value by estimation of infection is considered to be 6mg · min/L at the maximum.

(2) Influence of pH

In the excystation test, an experiment was conducted under the conditions of water temperature of 20°C, residual ozone levels of 0.1, 0.3 and 0.5mg/L and pH 6, 7, 8 and 9. The $1\log_{10}$ inactivated CT values were scattered about 5.5 to 9.0mg · min/L at the residual ozone level of 0.5mg/L, but were 6.3 to 7.6mg · min/L at the residual ozone level of 0.1mg/L and 6.7 to 6.9mg · min/L at the residual ozone level of 0.3mg/L, and no large difference existed. From these results, it is considered that the influence of pH does not exist under the condition of constant residual ozone.

(3) Others

Methodology has been investigated to estimate the inactivation level of animal infection with alternative methods such as excystation, DAPI/PI staining, etc., but these methods have not yet been sufficiently established. With the exception of specific organizations, there are many difficulties in introducing an estimation method by animal infection. From the viewpoint of the actual circumstances of the waterworks and sewerage fields in Japan, progress in research into the relation between both animal infection and alternative methods is desired.

2.2.2 Control of bromate ion formation

Bromate contamination, based on the guideline value of 25 μg/L in the WHO drinking water quality guideline (1993), has been determined to be a carcinogen, and in addition, the maximum contaminant level (MCL) of 10 μg/L was indicated by USEPA last year. These values are open to further discussion, but when raw water includes a high concentration of bromide ion due to the influence of sea water flowing against the stream, there exists a possibility that bromate ion exceeding these values is formed by ozonation.

To control this bromate ion, various research has been implemented. As an example, if the main goal of ozonation is to control trihalomethane formation, it has become clear that bromate ion formation can be controlled with the following method.

Fig.2 THMFP removal and bromate ion formation by ozonation

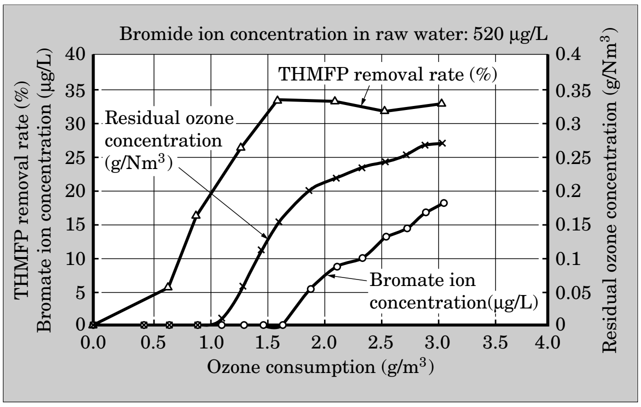
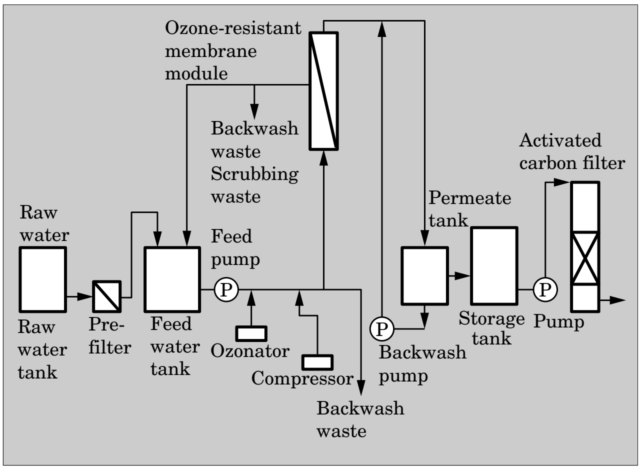


Fig.3 Schematic diagram of advanced water treatment system



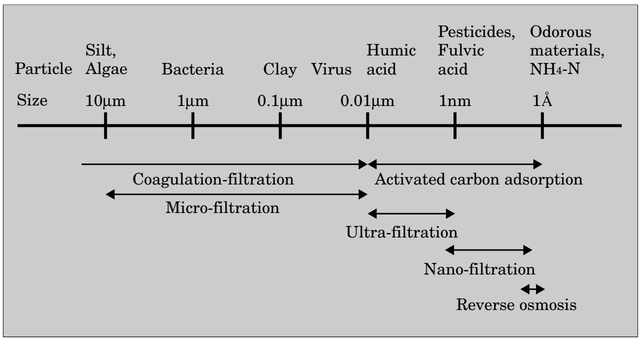
Bromate forming characteristics from the batch test shown in Fig. 2 indicate that ozone first reacts with the THM forming precursor followed by an increase of residual ozone in the treated water, and then the bromate ion is formed. From these characteristics, if residual ozone control is used for ozone dosage control and the residual ozone is controlled to approximately 0.1 to 0.2mg/L at the point where the residual ozone is a maximum, it is understood that the bromate ion formation will be restricted and sufficient removal of the THM formation ability will be obtained.

2.2.3 Advanced water treatment with ozone resistant MF membrane

Application has begun of micro-filtration (MF) membranes and ultra-filtration (UF) membranes to water purification, and these have been introduced into and are operating in more than one hundred small plants. In Europe and America, membrane filtration facilities have been already operating in purification plants of the several ten-thousands tons/day scale. In Japan, as a response to problems such as Cryptosporidium, it is considered that in the future, purification facilities using micro-filtration membranes and ultra-filtration membranes will be introduced into larger-scale purification plants.

On the other hand, due to the contamination of water resources, many purification plants are considering the introduction of advanced treatment facilities using ozone and biological activated carbon. In the advanced treatment MAC 21 project, a hybrid treatment of membranes and advanced treatment was also considered. However, when using organic membranes, deterioration of the membrane material became problematic, and therefore, the combination methods were limited. As a solution, a micro-filtration membrane using PVDF resistant to dissolved ozone as membrane material has been developed, enabling a more effective combination of membranes and advanced treatment (Fig. 3).

Fig.4 Particle size and separation method



(1) Ozone resistant membrane module characteristic
Type of membrane : Outer skin hollow fiber
Membrane material : PVDF (polyvinylidene fluoride)
Nominal pore size : 0.1 μm
Membrane area : 50 m^2

(2) Membrane treatment and effects with ozone resistant membrane

Presently, the membrane filtration equipment approved for water supply is the equipment that uses micro-filtration membranes and ultra-filtration membranes, and treats turbidity and disease-causing germs such as bacteria, Giardia and Cryptospordium. Conventional coagulation/sedimentation/filtration and membrane filtration basically treat the same substances. However, conventional technology treats water quality in mg/L orders, but in principle, membrane filtration perfectly removes particles larger than the pore size of the membrane. Since Cryptospordium has the possibility to cause disease even when there are several oocysts in 1 m^3 of water, conventional treatments may be difficult for operation and control. On the other hand, conventional treatments may surpass membrane filtration in such water quality criteria as color components.

Membrane filtration has the feature of perfect removal of impurities larger than the pore size as shown in Fig. 4, and in addition, the use of coagulant is zero or very small and the area for the facility can be reduced. However, membrane filtration must be combined with advanced treatments such as activated carbon adsorption for substances such as odorous substances and pesticides that are difficult to remove with micro- or ultra-membrane filtration. Of the various combination methods, use of ozone resistant membranes is considered as a method that limits clogging and fouling of the membrane while utilizing the feature of membrane filtration. Use of ozone as a pre-treatment of membrane filtration promotes the insolubility of metallic salts, coagulation of impurities in raw water, decomposition of sticky organic matters, and limits clogging and fouling of the membrane. Further, by keeping the dissolved ozone concentration on the surface of the membrane, the multiplication of organisms on the surface is prevented and organic substances adsorbed on the surface or inside of the membrane are decomposed. As a result, a high flux can be maintained. Currently, a high flux of 5m/day per unit of transmembrane pressure, 4 to 5 times greater than the conventional membrane filtration for waterworks, is obtained in water with ozone dosing of 2mg/L. Moreover, the frequency of cleaning the membrane with chemicals is remarkably reduced, facilitating operation and maintenance control. As for the water quality, good water treated with advanced treatment is obtained by combining ozonation and activated carbon.

Table 2 Sewage advanced treatment and Fuji Electric's technology

Advanced treatment	Fuji Electric s technology
Nitrogen and phosphate removal	○ A2O process control system ○ MLE nitrification-denitrification process with coagulant control system ○ Dual tank type intermittent aeration ○ Dual tank type intermittent aeration with membrane separation
Disinfection of treating water	○ Ozone disinfection
Reuse of treated water	○ Ozonation ○ Advanced oxidation process (AOP)

3. Advanced Water Treatment for Sewerage

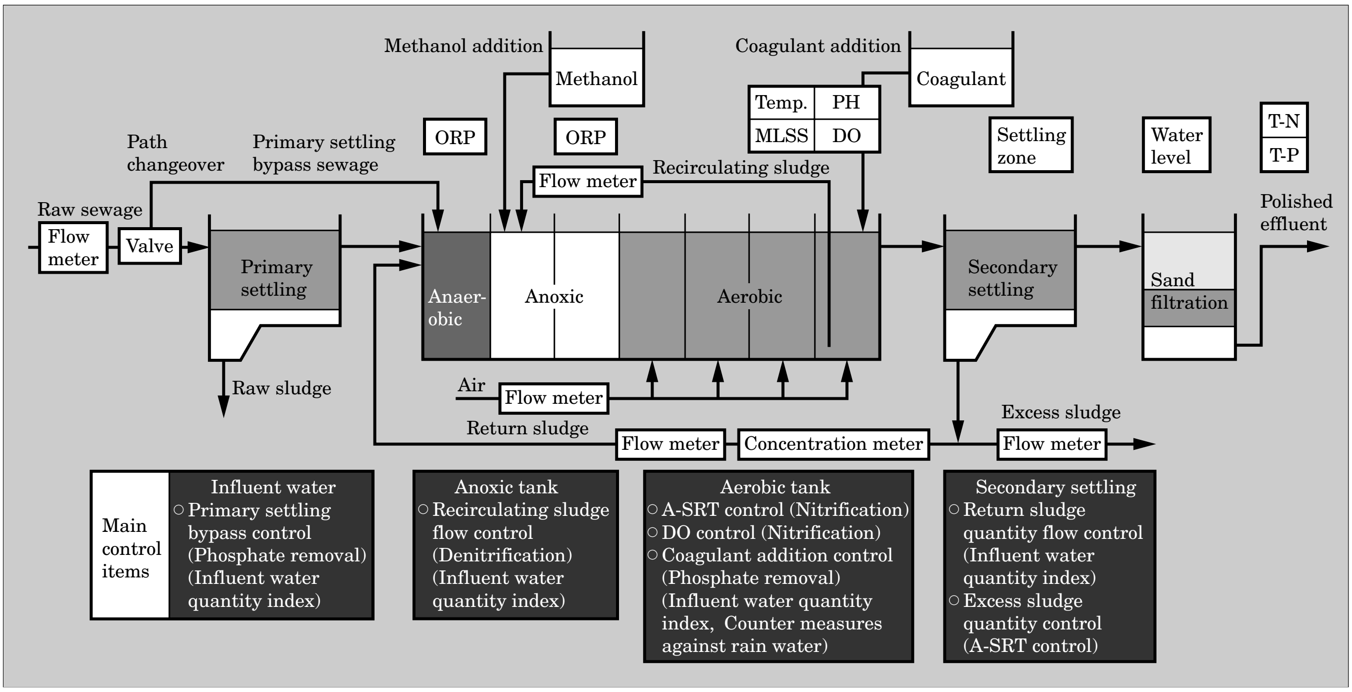
3.1 Nitrogen and phosphate removal

Advanced water treatment for sewerage and the technology of Fuji Electric is shown in Table 2. Regarding nitrogen and phosphate removal, representative of advanced treatment technologies, Fuji Electric has accumulated many good results for process control systems of the anaerobic-anoxic-aerobic method (A2O) and Modified Ludzack-Ettinger (MLE) process with coagulant.

Figure 5 shows an overview of the process control systems of the anaerobic-anoxic-aerobic method. Nitrogen removal consists of 2 stages of nitrification and denitrification, and performs A-SRT control that controls the removal of excess sludge to stabilize the nitrification and the restoration of sludge to efficiently denitrify, etc. Phosphate removal can perform primary sedimentation bypass control to maintain a high-level of phosphate removals corresponding to variations in the inflow water quality, coagulant adding control, etc. Highly reliable control is a feature of Fuji Electric's technology.

In addition to the above-mentioned controls, computer based technology is developing to simulate the behavior of organisms in each reaction tank related to nitrogen or phosphate removal, and to predict the treated water quality. It is believed that the introduction of this simulation technology will lead to the

Fig.5 Anaerobic-anoxic-aerobic process control system



realization of greater stability in the operation of advanced treatment processes.

Fuji Electric has independently developed a dual tank type intermittent aeration process and dual tank type intermittent aeration process with membrane separation as advanced treatment processes for small-scale treatments. A flow diagram of the dual tank type intermittent aeration process with membrane separation, the most advanced treatment process, is shown in Fig. 6. This process repeats aeration and stirring and creates anaerobic-anoxic-aerobic conditions in a time series using the oxidation reduction potential (ORP) as a control index to remove nitrogen and phosphate simultaneously in each reaction tank. Table 3 shows the results of domestic sewage. The treated water quality is very good as BOD and SS (suspended solids) are less than 1mg/L, T-N is 5mg/L and T-P is 0.1mg/L. In the future, these advanced treatments will be widely introduced.

Fig.6 Flow diagram of dual tank type intermittent aeration process with membrane separation

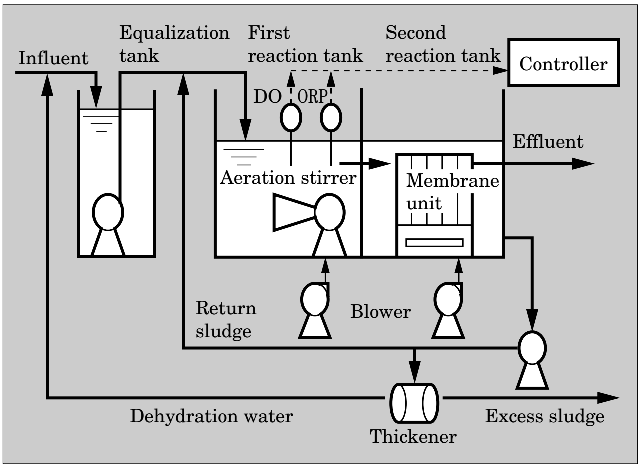


Table 3 Pilot plant treatment results for dual tank type intermittent aeration with membrane separation

Item	Influent water	Treated water	Removal ratio
BOD (mg/L)	181	<1	99% or more
COD (mg/L)	93	5.9	94%
SS (mg/L)	120	<1	99% or more
T-N (mg/L)	42	5.0	88%
T-P (mg/L)	4.5	0.1	97%

Fuji Electric has been actively dealing with the ozonation of sewage and has accumulated much experience with ozone disinfection that is harmless to the ecology in the discharge area and suitable for the reuse of treated water.

3.2 Activated sludge process without excess sludge

Activated sludge process is widely used for wastewater that includes organic substances. This is an

Fig.7 Flow diagram of activated sludge process without excess sludge

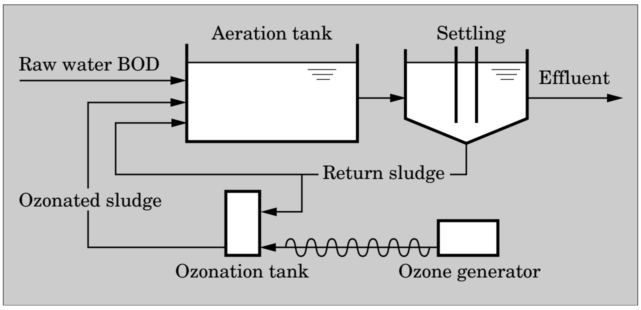


Table 4 Pilot plant test results

	Item		Treatment with additional ozone	Conventional treatment without ozone
Experimental conditions	Quantity of water treated (m^3/day)		10	10
	Retention time in whole aeration tank (h)		24	24
	Aerobic tank (h)		12	12
	Anaerobic tank (h)		12	12
	MLSS concentration (mg/L)		3,000 to 4,500	2,500 to 4,500
	Sludge return ratio (%)		36	36
	Water recirculation ratio (%)		16	16
	Ozone treatment sludge (m^3/day)		0.36	—
	Ozone dosage			
	for treating sludge (kgO$_3$/kg VSS)		0.05	—
	for treating water (mg/L)		16	—
Water quality		Raw water	Treated water	Treated water
	T-BOD (mg/L)	191	11.6	10.8
	S-BOD (mg/L)	32.6	1.7	1.0
	T-COD (mg/L)	122	20.0	13.6
	S-COD (mg/L)	28.3	14.2	7.5
	SS (mg/L)	240	19.6	10.3
	T-N (mg/L)	34.4	7.1	5.6
	NH$_4$-N (mg/L)	18.1	0.1	0.1
	NOx-N (mg/L)	0.0	3.4	2.2
	T-P (mg/L)	4.2	2.3	1.8
	PO$_4$-N (mg/L)	1.3	1.6	1.2
Sludge	Excess sludge quantity (kg/day)		0	ca. 0.7

excellent process that utilizes organism functions, but the multiplied organisms must be removed from the system as excess sludge and disposed of. In recent years, because of the increase of sludge quantity and the shortage of sludge disposal areas due to higher sewerage saturation levels, it is strongly desired to reduce the excess sludge quantity. As a countermeasure to this problem, a new activated sludge process has been developed.

Figure 7 shows the basic flow diagram of the process. A constant quantity of activated sludge is pulled out through a return sludge line and returned to an aeration tank after treatment with ozone. The principle of this process is that the activated sludge is converted to organic matter able to biologically decompose due to the strong oxidation reaction of ozone in an ozone reaction tank. This organic matter becomes food for the activated sludge in the aeration tank and decomposes into water and carbon dioxide, without creating sludge.

Table 4 shows experiment results in a pilot plant for 5 months where identical raw water has been treated both without and with additional ozone for comparison.

4. Conclusion

We introduced some of the concepts and Fuji Electric's technologies for advanced water treatment in waterworks and sewerage system. At Fuji Electric, we will continue to employ new technology and to develop more efficient and more highly advanced treatment systems in the future.

e-Front runners