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Simulation of the operating conditions of the municipal wastewater treatment plant at low temperatures using a model that includes the IAWPRC activated sludge model

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INTRODUCTION

One of the most suitable plans regarding the sewage system is for its use to transport and melt snow in snowy regions. Since this would cause a drop in sewage temperature, adequate conditions of operating biological wastewater treatment plants at low temperatures should be simulated. To determine the influence of melting and transporting snow by sewer, plant performance should be measured by the effluent water quality, and the quality and quantity of sludge produced from a plant, because the plant treats both water and sludge. This simulation requires the modeling of all unit processes in the municipal wastewater treatment plant: water treatment processes including primary and final clarification and aeration basin and sludge treatment processes.

The IAWPRC activated sludge model (Henze et al., 1987) has been frequently used to predict the performance of water treatment processes, especially of biological reactions. Singrist and Tschui (1992) calibrated the activated sludge model using municipal wastewater treatment plants in Switzerland. It is recognized that the IAWPRC model has applicability as a prognostic tool (Pedersenn and Sinkjaer, 1992). Lesouef et al. (1992) showed the on-site calibration techniques, verified the model on the full-scale plant, and proposed optimum reactor configurations for nitrogen removal. Therefore, the IAWPRC activated sludge model has been employed as the model of biological reactions in this work.

As for the model of unit processes other than biological ones, Dupont and Henze (1992) proposed the secondary clarifier model combined with the activated sludge model. It seems that few have attempted to model the entire water and sludge flow of a full-scale plant. The objectives of this paper are

- to verify the applicability of the IAWPRC model to the aeration tank of the plant at low temperatures using the pilot plant data,
- to show a simple method of modeling a sludge treatment process based on plant operation data,
- to draw operation maps of a full-scale plant in Sapporo at the presumed low temperature.

CALIBRATION OF THE IAWPRC MODEL USING THE PILOT PLANT DATA

Pilot plant experiments The pilot plant had a fully mixed aeration tank (1.2m^3) and a secondary clarifier, and it treated the primary effluent (2.6 L/min) of the Sapporo Sosei treatment plant. Experiments were performed at 5, 6.5, 8 and 10°C. The measured variables were BOD, COD, nitrogen compound of influent and effluent of the plant, volatile and non-volatile suspended solids of mixed liquor and return sludge at steady state.

Calibration of the IAWPRC model The model was calibrated using experimental data from operation at 10°C. Only two parameters, the yield for the heterotrophic biomass Y_H and the maximum specific growth rate for the autotrophic biomass μ_A, were adjusted from the default values (Henze et al., 1987). Y_H was 0.715 g cell COD formed (g COD oxidized)$^{-1}$ (default value 0.67). μ_A was 0.29 day^{-1} (default 0.3). RUN1 in Table 1 shows the computed and observed results. Then, temperature coefficients in the reaction equation were estimated using the data from operation at 5°C. Reducing the temperature coefficient for the growth of autotrophic biomass from 1.103 (default) to 1.044 yielded the results in RUN2 in Table 1.

Verification of calibrated parameters using data from operation at other temperatures Comparisons of the simulated results with data from operation at other temperatures (RUN3 and RUN4 in Table 1) showed that the IAWPRC model could be used for expressing biological reactions in the aeration basin at low temperatures.

TABLE 1 COMPARISON OF COMPUTED RESULTS WITH PILOT PLANT DATA

	RUN1		RUN2		RUN3		RUN4	
Temp.°C	10.3		4.9		7.7		6.5	
R_S *1(%)	30		30		33		31	
R_e *2(%)	1.28		1.08		2.02		0.77	
	observed	computed	observed	computed	observed	computed	observed	computed
BOD_T *3	7.1 *6	9.5	8.9	12.8	7.4	10.1	3.2	8.7
T-N	21	22.8	18.3	17.2	15.9	24.0	13.6	18.0
NH_4-N	17.5	19.1	11.5	12.6	12.5	22.6	8.1	7.8
NO_3-N	2.54	2.83	3.23	3.56	0.93	0.18	4.81	9.4
MLDO *4	1.3	1.55	3.4	3.9	2.5	4.4	1.9	0.7
MLSS	1430	1330	1270	1220	985	980	1810	1720
MLVSS	79.5%	78.1%	79.2%	83.9%	82.2%	77.8%	77.3%	75.6%
RSSS *5	5530	5520	4620	5050	3910	3700	6880	7050
SRT(day)	5.8	5.4	6.3	6.2	3.2	3.8	9.5	8.8

*1:R_S=[sludge recycle flow rate]/[sewage flow rate into plant]. *2:R_e=[excess sludge flow rate]/[sewage flow rate into plant]. *3:BOD was measured after addition of ATU. *4:MLDO is DO in the aeration basin. *5:RSSS is suspended solids concentration in return sludge. *6:Unit not specified in table is g/m³.

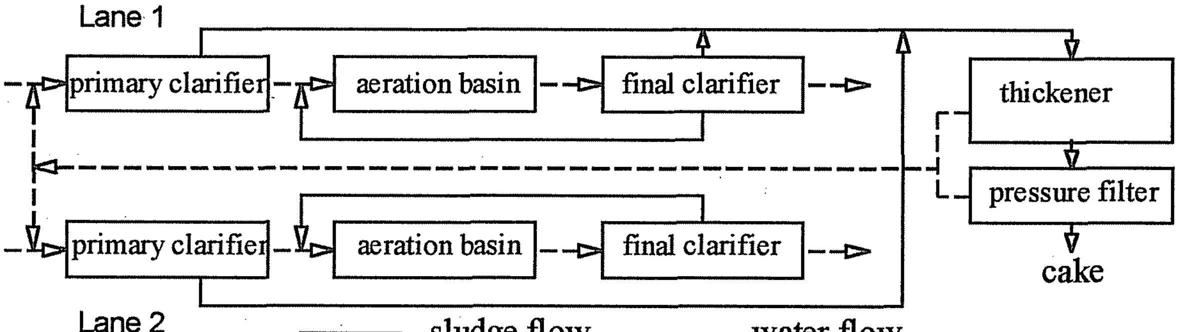

Fig. 1. Sludge and water flows in the investigated plant

SIMULATION MODEL FOR THE FULL-SCALE DOMESTIC WASTEWATER TREATMENT PLANT

Description of the investigated treatment plant The plant (Fig.1) treats wastewater of about 93500m³/day during dry weather in winter. This plant has two lanes in its water treatment system, and one sludge treatment system. Each water treatment lane consists of primary clarifiers, aeration basins and final clarifiers. Nitrification occurs partly in lane 1 and fully in lane 2 in winter. The sludge treatment system has gravity thickeners and pressure filtration units. 80% of cake from this system are incinerated. Supernatant of thickeners and filtrate is returned to the water treatment system. All water and sludge flows in Fig.1 were modeled in the simulation.

Primary clarifier A Voshel & Sak type formula (Voshel and Sak, 1968) was used. This empirical model shows that solid removal efficiency r is directly proportional to a power function of the influent solid concentration X_{in} and inversely proportional to a power function of the overflow rate L_P. Regression analysis using plant data yielded the following relationships:

$$r=0.133X_{in}^{0.312}L_P^{-0.0265}\ (Lane\,1),\qquad r=0.200X_{in}^{0.290}L_P^{-0.0807}\ (Lane\,2) \tag{1}$$

Figure 2 shows that Eq.(1) can explain the solid removal efficiency of the primary clarifier in the investigated plant. The solid concentration of the sludge from the primary clarifier was estimated by the following flow volume and solid mass balance equation at steady state:

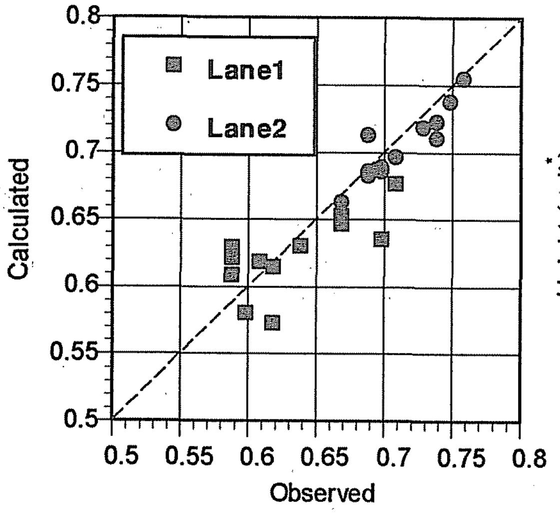

Fig.2. Comparison of calculatedresults of solid removal efficiency with plant data

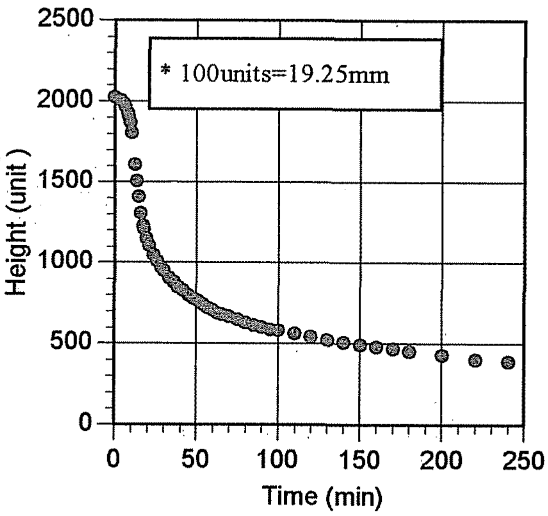

Fig.3. Settling curve of sludge in pilot plant at 5°C

$$Q_{in}=Q_e+Q_u, \qquad Q_{in}X_{in}=Q_eX_e+Q_uX_u \tag{2}$$

where Q_{in}, Q_e and Q_u are flow rates of influent, effluent and sludge, respectively. and X_{in}, X_e and X_u are concentrations of suspended solids.

In Eq.(2), flow rate of sludge Q_u was fixed at 3% of influent flow rate in the simulation, which was the average value of the plant operation data.

Aeration Basin Biological reactions in the aeration basin were described by the IAWPRC model. Prameters in the model had values estimated by the pilot plant data. The flow scheme of the basin was approximate, with 4 complete mixing tanks in series.

Final Clarifier The final clarifier had two functions: clarification and thickening. The models of clarification proposed so far relate effluent concentration of suspended solids to both the flow rate and the concentration of suspended solids of the influent. A typical empirical model has the following equation (Chapman, 1984):

$$X_e=a_1+a_2X_{in}+a_3L_P \tag{3}$$

The application of Eq.(3) to the plant data did not yield a close correlation. Since the plant data varied randomly, we set a constant value, 7.5 (g/m^3), for concentration of suspended solids of the effluent in the simulation. For thickening, the balance equations of flow volume and solid mass at steady state were employed in the same manner as the model of primary clarifier.

Thickener The outputs of the thickener are supernatant and concentrated sludge. The solid recovery percentage, $R_{TH,mass}$ (=[concentrated solid mass] / [input solid mass]), was adapted to measure of thickening performance. The mean value in winter, about 80%, was used in the simulation. The operational condition was specified by the withdrawal percentage $R_{TH,Q}$(=[concentrated sludge flow rate] / [input flow rate]). Plant data showed that $R_{TH,Q}$ had a constant value of about 10%. The balance equations of flow and solid mass:

$$Q_e=(1-R_{TH,Q})Q_{in}, \qquad X_eQ_e=(1-R_{TH,mass})X_{in}Q_{in} \tag{4}$$

yielded the flow rate Q_e and solids mass concentration X_e in supernatant. The concentration of dissolved matter in supernatant was specified by the plant data.

Besides computation by these balance equations, the minimum required cross-sectional area A_{Req} was calculated by limiting flux theory. By this area, one can examine the possibility of whether or not the desired concentrated sludge can be obtained by the thickening process in the simulation. Since this calculation requires a hindered settling velocity, the velocity and solids concentration relationship was specified by the settling test with the sludge from the pilot plant operating at 5°C. The analysis of the settling curve in Fig. 3 by Kynch's (1952) theory yielded the hindered settling velocities. These velocities were correlated by the logarithmic model, and the limiting flux G_L was computed by the following equations (Baskin, Suidan, 1985):

$$V=V_0\left(\frac{C}{C_0}\right)^{-n},\quad \frac{G_L}{V_0C_0}=(n-1)\left(\frac{n}{n-1}\right)\left(\frac{U}{V_0}\right)^{\frac{n-1}{n}} \tag{5}$$

where U is underflow velocity.

The settling test showed that the parameters in Eq.(5) were n=4.0, V_0=5.0 (cm/min), and C_0=1.0 (g/L), respectively. Solid mass and volume in withdrawal flow can be written as

$$A_{Req}G_L=X_{in}Q_{in}R_{TH,mass},\qquad A_{Req}U=Q_{in}R_{TH,Q} \tag{6}$$

Substituting Eq.(5) in Eq.(6) and rearranging the resulting expressions yields

$$\frac{A_{Req}}{R_{TH,Q}Q_{in}/V_0}=(n-1)\left(\frac{n}{n-1}\right)^{\frac{1}{n}}\left(\frac{X_{in}}{C_0}\right)^{n}\left(\frac{R_{TH,mass}}{R_{TH,Q}}\right)^{n} \tag{7}$$

Stokes law was assumed for the settling velocity and the temperature dependence of settling velocity was expressed by the viscosity μ, that is, V_0 at t°C, $V_0(t)=(\mu(10)/\mu(t))V_0(10)$.

Pressure Filter Coagulants in the plant are ferric chloride and lime. The average addition rates in winter were about 7% and 31%. There were few variations in the water content of cake and a constant value, 63%, was used in the simulation. The solid recovery percentages were nearly constant, about 90%. The heating value of cake was calculated by the experimental formula (Murakami et al., 1986);

$$H_C=(1-w/100)H_{l,k}-540w/100 \tag{8}$$

$$H_{l,k}=0.93\left(\frac{(58.3X_{CAKE}-193)-353(k_2-0.69k_1)}{1+k_2-0.03k_1}\right)-33 \tag{9}$$

where H_C is heating value of cake (kcal/kg-cake), w is water content of cake (%), X_{CAKE} is organic matter content in cake (%), and k_1 and k_2 are respective addition rates of ferric chloride and lime.

This heating value of cake was the measure of burning characteristics in the simulation. Murakami et al. (1986) reported that the lower limit of heating value for combustion without fuel depended on the type of incinerator. In the simulation, 430kcal/kg-cake was used for the lower limit.

Comparison of simulated results with plant data results We simulated average performance in winter by steady state analysis and compared the results with plant data. Influent concentrations used in the simulation are summarized in Table 2. The comparison in Table 3 shows that the simulation model yielded the reasonable results.

TABLE 2 INFLUENT CONCENTRATION USED IN SIMULATION (g/m³)

Readily biodegradable COD	Soluble inert COD	Slowly biodegradable COD	Particulate inert COD	Oxygen
70	10	120	30	5
NH_4-N	NO_X-N	Soluble Org-N	Particulate Org-N	non-volatile SS
16.0	0.3	4	4	60

PLANT OPERATION MAPS AT 4 AND 8°C

It was expected that the melting and transporting snow by sewer would cause influent temperatures to fall to 4-8°C. The operation maps of the plant at 4 and 8°C were drawn by the simulation of the steady state. The operational variables were the sludge recycle rate ([sludge recycle flow rate]/[sewage flow rate into plant]) R_s and the excess sludge withdrawal rate ([excess sludge flow rate]/[sewage flow rate into plant]) R_e. The goal of operation was specified by the following four variables:

TABLE 3 COMPARISON OF SIMULATED RESULTS WITH PLANT DATA

	LANE 1		LANE 2	
flow rate	$42700 m^3/day$		$50800 m^3/day$	
R_S *1, R_e *2	26%, 1.3%		31%, 0.77%	
	observed	computed	observed	computed
BOD_T *3	3.4 *6	6.2	3.5	6.2
T-N	13.9	14.8	12.1	16.3
NH_4-N	6.3	5.4	0	0.6
NO_3-N	7.6	9.0	11.7	15.4
MLDO *4	2.8	2.9	5.2	5.2
MLSS	1980	1660	2650	2450
MLVSS	72.0%	70.5%	71.0	71.3%
RSSS *5	8050	7700	9560	10130
sludge	observed		computed	
thickener input	24.2 t/day		27.5 t/day	
cake	24.4 t/day		25.6 t/day	
heating value	585 kcal/kg-cake		520 kcal/kg-cake	

*1: R_S=[sludge recycle flow rate]/[sewage flow rate into plant]. *2: R_e=[excess sludge flow rate]/[sewage flow rate into plant]. *3:BOD was measured after addition of ATU. *4:MLDO is DO in the aeration basin. *5:RSSS is suspended solids concentration in return sludge. *6:Unit not specified in table is g/m^3

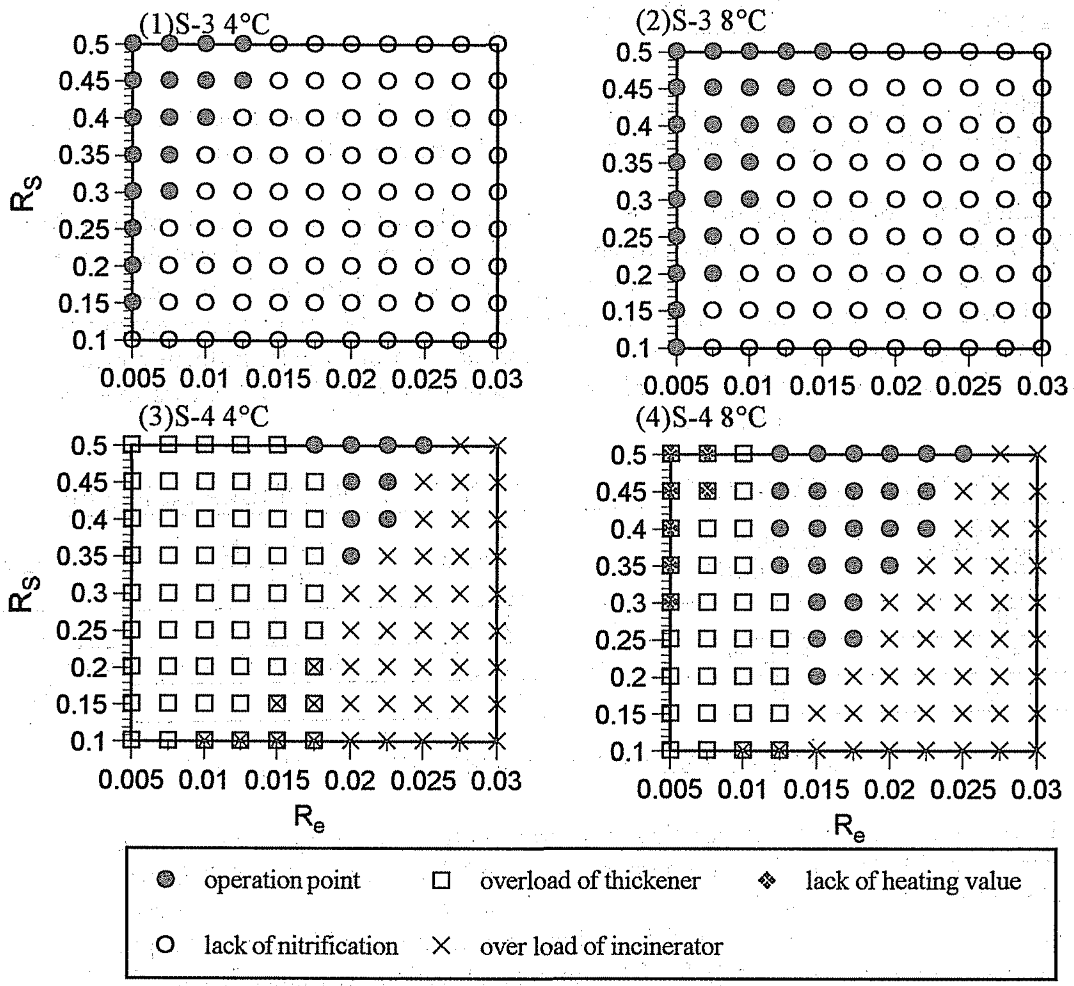

Fig. 4. Plant operation maps

-nitrate nitrogen concentration in effluent,
-the minimum required cross-sectional area of thickener,
-cake production mass rate,
-heating value of cake.

We prepared four kinds of scenarios and searched the available operating conditions in each case:

S-1: Keep the present level of nitrate nitrogen concentration in effluent.
Neither thickener nor incineration plant has an excess capacity.

S-2: Keep the present level of nitrate nitrogen concentration in effluent.
Both thickener and incineration plant have 10% excess capacity.

S-3: Keep the present level of nitrate nitrogen concentration in effluent.
There is no limitation either in thickener or in incineration.

S-4: No limitation on nitrification.
Both thickener and incineration plant have 10% excess capacity.

In S-1, no available operating point was found at 4°C or at 8°C. In S-2, very few operating points were obtained only at 8°C. Figure 4 shows the operation maps of S-3 and S-4. In S-3, available operating points correspond to the small R_e, that is, long SRT operation. The operating conditions in S-4 at 8°C are in a wide range and include the present plant operating points. At 4°C in S-4, a large R_s is required, and this might cause some troubles with the final clarifier. The difference between maps of S-3 and S-4 shows that it is impossible to keep nitrifying bacteria at the present level in the plant while preventing excess load for sludge treatment. This suggests that the enlargement of the sludge treatment system or that the addition of nitrifying-bacteria-holding apparatus to aeration basins is required.

CONCLUSIONS

A simulation model was developed of the full-scale municipal wastewater treatment plant at a steady state was developed. Processes included in this model are those of primary clarifier, aeration tank, final clarifier, thickener and pressure filter. The IAWPRC model was used for simulation of reactions in the aeration basin. This model was calibrated using the data of 5 and 10°C pilot plant experiments. The calibrated model was able to predict the results of other temperature experiments at the pilot plant. The full scale plant model yielded fairly accurate results on the sludge mass load of thickener, production rate and heating value of cake as well as on nitrification of the municipal wastewater plant in winter. Plant operation maps at 4 and 8°C were drawn. They showed that the enlargement of the sludge treatment system or the addition of nitrifying-bacteria-holding apparatus to aeration basins is required to maintain the present treatment level if the sewage system is used for melting and transporting snow.

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