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Automatic Control Of Dissolved Oxygen In Activated Sludge Aeration Tank

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The quality of the effluent from an activated sludge aeration tank can deteriorate when the substrate removal rate decreases due to an abrupt reduction in the DO concentration, which is affected by such operating conditions as the loading rate, temperature, wastewater composition, and so on. In this research, a DO control system that includes a PI (proportional-integral) controller/Hiraoka controller was developed and applied to a pilot-scale activated sludge process, then its acceptability was estimated. The applicability of the respiration rate to DO control was also estimated. The respiration rate indicated a variety of input organic loading rates, which is the main disturbance to the DO concentration in an aeration tank. When the influent concentration incrementally decreased and increased between COD_{cr} 1,000 mg/l and 100 mg/l, the control system with a PI controller exhibited a good performance - the average DO concentrations were 2.00±0.14 mg/l and 1.88±0.15 mg/l (set value was 2.0 mg/l), respectively, and the settling time was just 10 minutes. When the control system was operated for 4 days, the DO concentration was 1.99±0.18 mg/l and 32.6 % of the air flowrate was saved. However, the fluctuations in the respiration rates and air flowrates were severe, which could be harmful to the stability of the biomass and mechanical stability of the blower. A possible approach to solve this problem may be the simultaneous control of the loading rate and DO concentration.

Key words : DO control, activated sludge, PI controller, loading rate, respirometry

1. Introduction

In an aerobic biological wastewater treatment process such as activated sludge, dissolved oxygen is a major parameter for the growth of the biomass and the substrate. When the amount of dissolved oxygen is deficient, the biomass activity decreases, which causes a deterioration in the quality of the effluent, and filamentous microorganisms become the dominant species. In contrast, when oxygen is oversupplied, the biomass floc is destroyed and the settlability of the biomass deteriorates. Generally, an aeration tank is operated in a state of over-aeration to maintain a high DO concentration, which requires a high amount of energy. As a result, the problem of improving the quality of the effluent while also saving energy has recently received much attention and the importance of automatic control in wastewater treatment plants has increased resulting in the proposal of many DO control strategies (Evans and Laughton, 1994).

One attractive DO control strategy is only aerating an aeration tank to ensure time-varying oxygen consumption. Aeration costs can account for up to 50% of the total energy consumption in a wastewater treatment plant and are about 4 times higher than pumping costs, the second-highest energy consuming process (Evans and Laughton, 1994). In a mega-scale wastewater treatment plant where the personal equivalent (P.E.)

is over 100,000 persons, the electricity consumed for aeration is about 30 kWh/P.E (Balmer and Mattsson, 1994).

It has been previously reported that, in a bench-scale experiment, 60~77% of the aeration cost could be saved through DO control (Lee and Sung, 1996). When an advanced on-line DO control was applied to a full-scale wastewater treatment plant, 40% of the total operating cost was saved (Nielsen and Önnerth, 1994). Furthermore, when a DO control system was applied to a 3,800ton/day-capacity wastewater treatment plant, $65,500(U.S.) of the maintenance cost was saved per year, and $36,300 was saved, when considering depreciation (Flanagan et al., 1977).

In Korea, DO control systems have rarely been applied to sewage/wastewater treatment plants, except for a food industry wastewater treatment plant (Nam et al., 1996) and coke wastewater treatment plant (Lee et al., 1997). As a result, the DO concentration in most wastewater treatment plants is still controlled by the operator's judgement.

In this study, a DO control system was installed to a pilot-scale activated sludge aeration tank, and a PI controller and Hiraoka controller (a special type of PI controller) were then compared for their feasibility and stability during operation (Hiraoka and Tsumura, 1992).

2. MATERIALS AND METHODS

2.1. Pilot-Scale DO Control System

The experiments were carried out in a pilot-plant scaled down to 1/1,200 of a field-scale pigment wastewater treatment plant. The pilotplant included an activated sludge system, consisting of a mixing chamber, measuring devices such as a DO meter, MLSS meter, and respiration analyzer, a control panel, and a computer and electrical communication parts. The aeration tank had **four** 750 L compartments and the HRT was maintained as 34 hours. Primary treated wastewater from a field plant that was pH conditioned and air floated was used as the raw wastewater (Fig. 1).

For on-line measurements of the DO concentration, MLSS concentration, and biomass respiration rate in the aeration tank, a DO meter (Züllig, S12H), MLSS meter (Züllig, COSMOS-FH), and respiration analyzer (Manotherm, RA-1000) were all installed in the first compartment. The air flowrate to the aeration tank was measured with an air flow meter (FLT-N). Another respiration analyzer was used for measuring the input substrate loading rate **(Kim et al., 1995)**.

Data from the DO meter, MLSS meter, and respiration analyzer were transmitted to the control panel through an analogue cable and then transmitted to a personal computer after digitization by an A/D converter. The data output from the computer was transformed to an analog current of 0~20 mA by a D/A converter and then retransformed to a 50~360 Hz frequency before being transmitting to the blower motor.

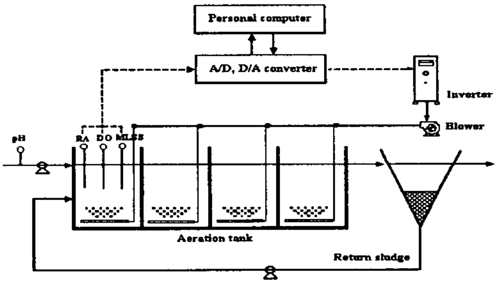


Fig. 1. Schematic diagram of pilot-scale activated sludge system and DO control system.

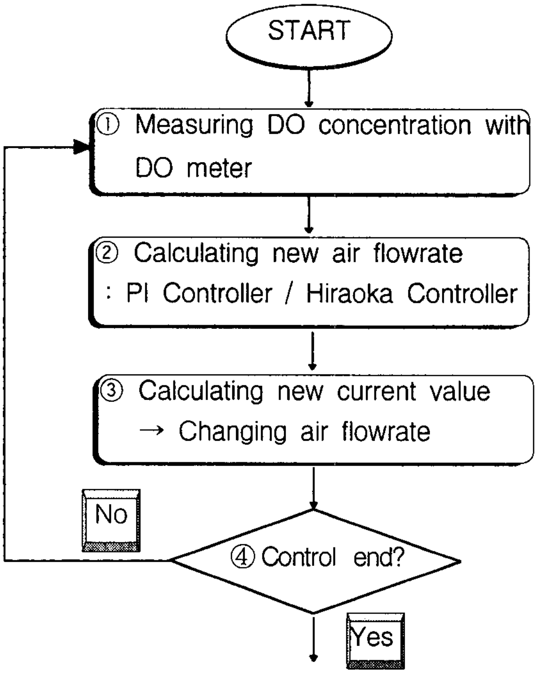
2.2 Feedback DO Control Algorithm

A PI controller and the controller proposed by Hiraoka and Tsumura (1992) were both used for the feedback DO control system (Fig. 2). In the case of the PI controller, the error (E) between the set point (DO_{sp}) and the measured value (DO_n) was calculated and multiplied by the control time, **thereafter** a cumulative error value (S_n) was calculated. The cumulative error value multiplied by the integral gain (I) was then combined with the error value (E) multiplied by the proportional gain (P). This summation value was combined with the prior air **flowrate** (AQ_{n-1}) to produce a new air **flowrate** (AQ_n). In contrast, in the case of the Hiraoka controller, the coefficient "a" was multiplied by the error value between the prior measured value (DO_{n-1}) and the current measured value, and the coefficient "b" was multiplied by the error between the set point and the measured value. Both terms were combined with the prior air **flowrate** to produce a new air **flowrate**. In both controllers, the control time was 2 minutes. The program was made using Turbo C.

2.2 Experimental Method

In order to test the validity of the DO control system, five sets of experiments were carried out as shown in Table 1. Run #1 focused on observing the DO concentration variation in an aeration tank with a varied loading rate under a constant air **flowrate** without an automatic control system. Runs #2, #3, and #4 were focused on observing the DO concentration variation under each control algorithm with an artificial variation of the influent substrate concentration. In runs #2 and #3, the influent wastewater with COD_{cr} 600 mg/l was substituted by tap water for 3 hours. In run #4, however, diluted wastewater with COD_{cr} 100 mg/l was supplied to the aeration tank for 3 hours instead of raw wastewater. In the last run, the DO concentration was monitored for 4 days without any change in the artificial loading, plus the PI controller that exhibited the best performance in the prior tests was used.

In all the experiments, the DO set point was 2 mg/l, and the influent loading rate was monitored by measuring the actual respiration rate (Ra) of the activated sludge with a respiration analyzer. The pH value of the influent and temperature of the aeration tank was controlled within the ranges of 7.0 ± 1.0 and 20 ± 1 ℃, respectively.



<PI controller>

$$\begin{aligned} E &= DO_{sp} - DO_n \\ S_n &= S_{n-1} + E \times T \\ AQ_n &= AQ_{n-1} + P \times E + I \times S_n \end{aligned}$$

<Hiraoka controller>

$$\begin{aligned} AQ_n = &\ AQ_{n-1} \\ &+ a(DO_{n-1} - DO_n) \\ &+ b(DO_{sp} - DO_n) \end{aligned}$$

AQ : Air flowrate (m^3/hr)
E : Error value
T : Control time (min)
DO : Dissolved oxygen conc. (mg/l)
Sn : Accumulated error
P, I, a, b : Gain values

Fig. 2. Algorithm for DO control.

Table 1. Experiments for DO control

Run No.	Controller	Influent	COD (mg/l)
Run #1	Manual	Raw w/w	600 ~ 1,200
Run #2	Manual	Raw w/w + Tap water	600→0→600
Run #3	Hiraoka controller	Raw w/w + Tap water	600→0→600
Run #4	PI controller	Raw w/w + Tap water	1,000→100→1,000
Run #5	PI controller(long term)	Raw w/w	1,000 ~ 1,200

3 RESULTS AND DISCUSSION

3.1. Variation of DO Concentration under Manual Control (runs #1 and #2)

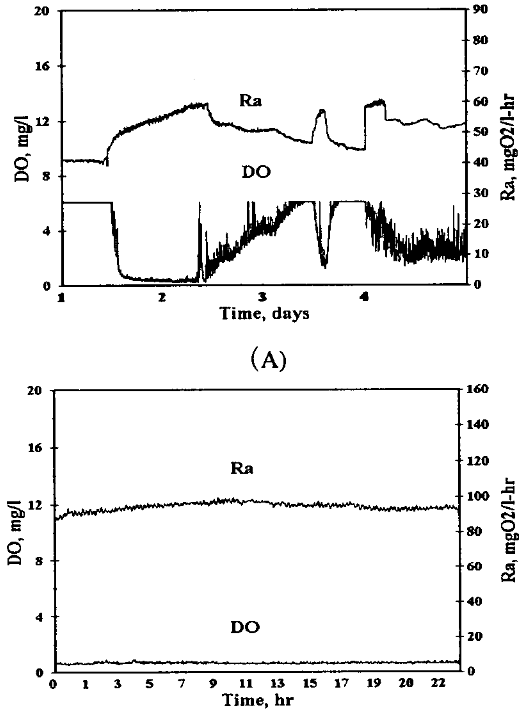
Figure 3 shows the variation of the DO concentration when the air **flowrate** was kept constant by manual control. When the air **flowrate** was maintained at 14 m^3/hr for 5 days (Figure 3(A)), the variation of the DO concentration was inversely proportional to the respiration rate. This is because the DO concentration was affected by the substrate removal rate represented by the respiration rate.

Even though the wastewater passed through equalization (HRT 20 hr) and air floatation (HRT 17 min) tanks, the variation in the respiration rate caused dramatic DO concentration changes. When the influent loading rate was low, the aeration tank was over-aerated. Conversely, when the rate was high, the DO concentration remained below 0.5 mg/l. Even though the air **flowrate** was increased from 14 m^3/hr to 23 m^3/hr, the DO concentration remained below 1.0 mg/l (Figure 3(B)). Accordingly, it was concluded that, when the air **flowrate** is controlled manually, the DO concentration cannot be maintained within the proper ranges, which can cause deficient DO concentrations or a loss of aeration.

Figure 4 shows the fluctuations in the DO concentration under the step change of organic loading. When the influent substrate concentration decreased from COD_{cr} 600 mg/l to 0 mg/l, the DO concentration increased dramatically from 2 mg/l to 6 mg/l. A flat DO concentration curve at 6 mg/l was caused by the upper limit of the transmitter, which was set to 6 mg/l to improve the accuracy of the output current.

3.3. DO Control with a Hiraoka Controller (run #3)

The results of the DO control experiment with a Hiraoka controller, using the same conditions as for run #2, are shown in Figure 5. When the tap water was introduced, the respiration and organic loading rates decreased, and the DO concentration increased. However, the air **flowrate** decreased rapidly with the control system, and the DO concentration remained around 2 mg/l after about 1 hour. The opposite behavior was observed when the raw wastewater was reintroduced to the aeration tank. In each mode, the average DO concentrations after 1 hour were 2.12±0.10 mg/l and 2.20±0.18 mg/l, respectively. The coefficient values "a" and "b" in the Hiraoka controller were both 1.5.



(A)

(B)

Fig. 3. Variation of Respiration rate and DO concentration with organic loading. (Q_{air}: 14 m^3/hr (A), 23 m^3/hr (B)).

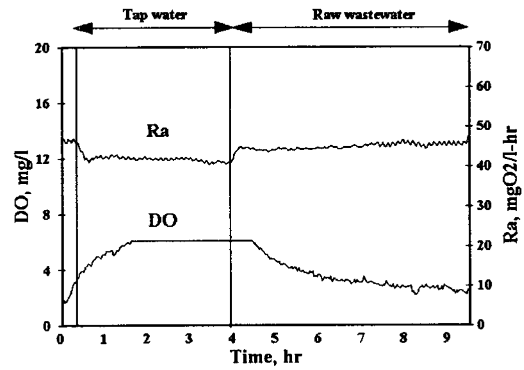


Fig. 4. DO concentration fluctuation under step change of organic loading.

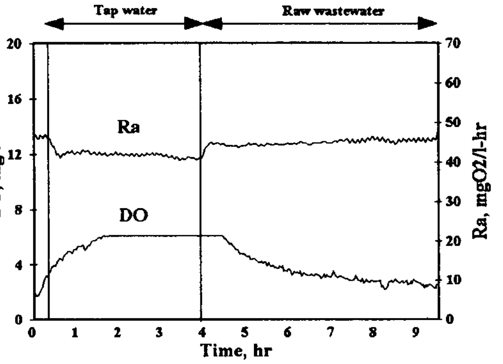


Fig. 5. Respiration rate and DO control based on a Hiraoka controller with an organic loading variation.

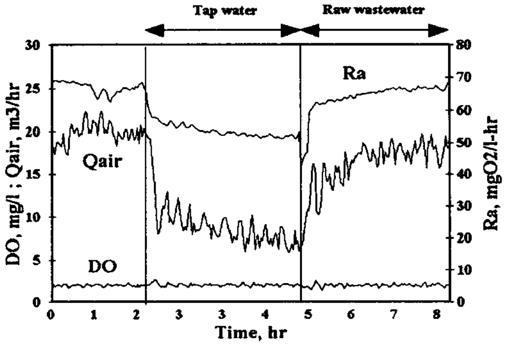


Fig. 6. Respiration rate and DO control based on a PI controller with a step loading variation (PI controller).

3.3. DO Control with PI Controller (runs #4 & #5)

Figure 6 presents the results of the DO control experiment that used a PI controller under similar experimental conditions to those used in runs #2 and #3. The variation pattern of the DO concentration was similar to that in the prior control experiments, however, it should be noted that the settling time was much shorter than that with the Hiraoka controller. Only about 10 minutes was required for the DO concentration to return to 2.0 mg/l. In each mode, the average DO concentration after 10 minutes was 2.0±0.14 mg/l and 1.88±0.15 mg/l, respectively.

Run #5 was performed for 4 days using continuous raw influent wastewater and a PI controller. The gain values P and I were both 1.5.

Over the 4 days, dramatic variations in the respiration rate occurred 10 times (Figure 7). This may have been caused by the various pigment products resulting in variations in the substrate concentration level and the composition of the wastewater. Nonetheless, the DO control system accomplished a DO concentration level around the set point, 2 mg/l. The average DO concentration was 1.99±0.18 mg/l, and 90% of the DO values fell within the range of 2.0±0.26 mg/l.

3.4. Economic Benefit and Mechanical Stability of DO Control System

In run #5, the DO concentration in the aeration tank was controlled by a PI controller for 4 days, and 32.6% of the air flow was saved when compared to a constant air flowrate of 23m^3/hr. Accordingly, as shown in Figure 7, the DO concentration in the aeration tank was successfully controlled by a PI controller. However, it should be noted that the degree of the air flowrate variation was quite substantial. The standard deviation of the air flowrate was 3.30m^3/hr, and this corresponds to 21.2% of the average air flowrate, 15.57 m^3/hr. This means that if this control system were applied to a full-scale plant, the variation in the electricity supplied to the blower would be significant and possibly damaging.

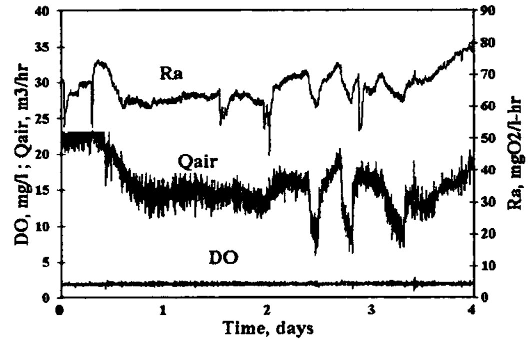


Fig. 7. Respiration rate and DO control based on a PI controller at a pilot pigment wastewater treatment plant.

As shown in Figure 8, as the gain value increases (Kc_I) in a PI controller, the settling time becomes shorter, however, there are more oscillations related to set point changes and overshooting increases.

Conversely, as the gain value decreases (Kc$_2$), overshooting decreases and there are fewer oscillations related set point changes, however, the settling time is longer(Stephanopouls, 1984). In this experiment, the oscillation depth was significant, therefore, it is recommended that the gain values be decreased. However, the electrical and mechanical stability of a blower cannot be improved by merely decreasing the P and I gain values, therefore, more research is needed on this problem. One possible focus for future research is the simultaneous control of the DO concentration and the respiration rate. The loading rate can be controlled on-line by measuring the respiration rate **(Kim et al., 1995)**. However, the respiration rate and DO concentration are interdependent. When the respiration rate increases, the DO concentration decreases, since both are effected by the organic loading rate. As a result, respiration rate control will affect the performance of DO control, plus, the simultaneous control of the DO concentration and the respiration rate is desirable to improve the stability of both the biomass and the blower.

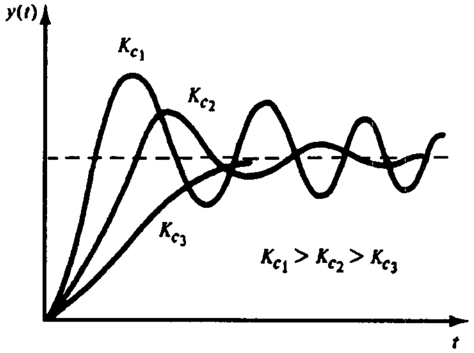


Fig. 8. Effect of gain on the closed-loop response of first-order systems with integral control only (Kc : gain value).

4. CONCLUSIONS

The main conclusions that can be drawn from this study are as follows: the DO concentration is significantly affected by the organic loading rate, which can be monitored by measuring the respiration rate, and is inversely proportion to the respiration rate. Since the influent substrate concentration of the pigment industry fluctuates quite frequently and dramatically, a stable DO concentration can not be achieved with manual control.

When a DO control system including a PI controller was adopted for the aeration tank, the DO concentration was maintained at 1.99±0.18 mg/l (set point 2 mg/l) even with substantial variations in the influent organic loading rate.

Although successful DO control was accomplished with the use of a simple PI controller, the electrical and mechanical loading on the blower was considerable and the fluctuation of the respiration rate was substantial, accordingly, the **simultaneous** control of the DO concentration and loading rate is recommended in order to improve the stability of the activated sludge process.

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REFERENCES

[1] Balmer, P. and B. Mattsson, 1994, *Water Science and Technology*, 30(4), 7-15.

[2] Lee, B.-K., Chun, H.-D., Sung, S.-W., 1996, *Journal of Korean Society of Environmental Engineers*, 18(12), 1535-1546.

[3] Evans, B. and P. Laughton, 1994, *Water Science and Technology*, 30(4), 17-23.

[4] Flanagan, M. J., B. D. Bracken, J. F. Roesler, 1977, *Journal of the Environmental Engineering Division, ASCE*, 103(EE4), 707-722.

[5] Hiraoka, M. and K. Tsumura, 1992, In *Dynamic and control of the activated sludge process*, Technomic Publishing Company, Inc., Lancaster, pp 169-206.

[6] Kim, C.W., B.G. Kim, T.H. Lee and E.H. Choi, 1995, Loading control system using actual respiration rate for activated sludge process, Proceedings of Specialized Conference on Sensors in Waste Water Technology, IAWQ, Copenhagen, Denmark.

[7] Lee, B. K., S. W. Sung, H. D. Chun, J. K.

Koo, 1977, Automatic control for DO and pH in the activated sludge process in a coke wastewater treatment plant, Proceedings of 7th international workshop on instrumentation, control and automation of wastewater treatment and transport systems, IAWQ, pp188-195, Brighton, UK.

[8] Nam, S. W., N. J. Myung, K. S. Lee, 1996, *Water Environment Research*, 68(1), 70-75.

[9] Nielsen, M. K. and T. B. Ønnerth, 1994, State of the art: control of activated sludge plants, **Proceedings** of workshop on Modelling and Control of Activated [10] Sludge Processes, IAWQ, Copenhagen, Denmark.

[10] Stephanopouls, G., 1984, In *Chemical process control: An introduction to theory and practice*, Prentice-Hall, Inc., New Jersey, pp 258-296.