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Comparison of Proportional, Integral, and P-I Control Systems in Biological Wastewater Treatment Plants

Sungpyo Kim[†]

Department of Civil, Structural, and Environmental Engineering,
State University of New York at Buffalo, Buffalo, New York, 14260, U.S.A.

생물학적 하수처리시스템에 적용된 Proportional, Integral 및 P-I 조절 시스템에 대한 비교

김성표[†]

뉴욕 주립 대 버펄로 대학 토목, 구조, 환경공학과

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Abstract

The main purpose of this study is to evaluate the characteristics of three sets of traditional control methods (proportional, integral, and proportional - integral controls) through lab-scale biological reactor experiments. An increase in proportional gain (K_c) resulted in reduced dissolved oxygen (DO) offset under proportional control. An increase in integral time (T_i) resulted in a slower response in DO concentration with less oscillation, but took longer to get to the set point. P-I control showed more stable and efficient control of DO and airflow rates compared to either proportional control or integral control. Developed P-I control system was successfully applied to lab-scale Sequencing Batch Reactor (SBR) for treating industrial wastewater with high organic strength.

keywords : Dissolved oxygen control, Proportional and integral control, Sequencing batch reactor (SBR)

1. Introduction

One of the most common methods to treat domestic wastewater is the activated sludge process (Metcalf et al., 1991). The activated sludge process removes organics in wastewater by maintaining an active microbial culture (biomass) under aerobic condition. The conventional control strategy for activated sludge processes has been to maintain desired levels of biomass and dissolved oxygen (DO) in the aeration tank. Control of oxygen is important because low dissolved oxygen concentration can lead to poor effluent quality. Maintaining a higher than needed level of dissolved oxygen in an aeration tank can hinder biomass floc formation in the process and reduce the biomass floc settling. In addition, use of excess oxygen generates costs which have no benefit (Ferrer et al.,1998). In the past, the experience of skillful operators has been an important factor in keeping optimum DO levels in the aeration tank. However in the 1970's, as new equipment was developed (computer, PLC etc), many studies have been conducted to evaluate automatic control of dissolved oxygen for process improvements and cost savings (Flanagan et al., 1977; Manning et al., 1980; Ferrer et al., 1998; Galluzzo et al., 2001). Olsson et al(1998) identified dissolved oxygen control as one of the most important control topics in water and wastewater treatment. Recently, many different types of DO control strategies have been proposed such as Proportional-Integral (P-I) control (Lee et al., 1998), nonlinear control (Lindberg et al., 1996), Fuzzy control (Galluzzo et al., 2001), etc. In addition, improved sensor technologies make broad dissolved oxygen control strategies (Alex et al., 2003). However, conventional process control strategies such as P-I control should be the first consideration when automatic control system is needed in a real wastewater treatment plant because of their simplicity and reliability. Even though much research has been conducted on the control of dissolved oxygen in the activated sludge process and other suspended growth systems, most of the research has been focused on the operating results of developed control logic to a process. However, there is little research for comparing and differentiating the characteristics of developed controls which were applied to environmental engineering processes. Therefore, the main purpose of this study is to provide the basic concepts for several traditional control methods

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[†] To whom correspondence should be addressed.
sk40@buffalo.edu

(Proportional control, Integral control and Proportional - Integral control), which are mostly used in practical process control. The results from this study will help to extend the knowledge of process control and provide a solid base for a developing enhanced control strategy.

2. Method and Materials

2.1. Bioreactor and DO control

The bioreactor was operated at room temperature which ranged from 22 - 24°C. To start the bioreactor, return activated sludge was collected from Amherst New York Wastewater Pollution Control Facility as a seed population. As shown in Table 1, 10 mL from each stock solution were diluted in 1 liter of tap water to make the feed.

Table 1. Stock solution composition of synthetic wastewater

Species		Concentration (g/L)
Stock Solution A	Glucose	93.8
	K_2HPO_4	320
	KH_2PO_4	160
	NH_4Cl	120
Stock Solution B	$MgSO_4 \cdot 7H_2O$	15
	$FeSO_4 \cdot 7H_2O$	0.5
	$ZnSO_4 \cdot 7H_2O$	0.5
	$MnSO_4 \cdot 3H_2O$	0.5
	$CaCl_2$	2.0

Influent COD concentration of the feed was 1000 mg/L. This feed was pumped continuously at 6.9 mL/min to maintain a 1-day hydraulic retention time in the bioreactor. A schematic diagram for the control system including the biological reactor is represented in Fig. 1.

As shown, DO control in the biological process is accomplished by a submerged DO sensor (Model 54A, Yellow Springs Instrument, Ohio), which detects the DO concentration in the bioreactor and sends it to the terminal through the DO meter. The terminal transforms the analog signal from the DO meter to a digital signal which is received by the computer data acquisition (D.A.Q.; Multifunction I/O Board for ISA, Model number: Lab-PC-1200, National Instruments) board. This DO signal is analyzed and the output digital signal is manipulated based on the controlling software. By adjusting the airflow pump speed, DO concentration in the aeration basin is controlled. The output signal for controlling the airflow pump is sent back to terminal where it is converted to analog and then flows to the airflow pump to control its speed.

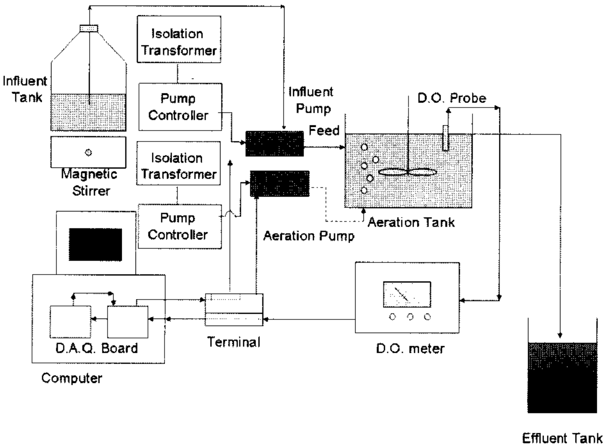

Fig. 1. Schematic diagram of bioreactor with DO control system.

2.2. Testing procedure of control action

To initiate a test, each DO control system (Proportional control, Integral Control, and Proportional and Integral Control) was adjusted until a constant 3 mg/L DO was achieved in the bioreactor. After the DO of the reactor reached the set point of 3 mg/L, continuous recording of the DO in the reactor and the airflow rate as an EXCEL file in the computer was initiated. After bioreactor operation was maintained for one hour with a DO at 3 mg/L, the influent flow rate was increased as a 1.5 step input. To record the response of the step input, dissolved oxygen and air flow rate were sampled every 20 sec. Dissolved oxygen and air flow rate data were collected continuously for 7-8 hrs after the step input. After operating at the higher flow rate applied during the test, the bioreactor was returned to baseline conditions. Between tests, the bioreactor was maintained at baseline conditions for a minimum of 12 hrs.

2.3. Control action equations

Table 2 summarized each theoretical control equation. Applied equations in this study were modified from these equations. Applied ranges of controller gain (K_c) and integral time (T_i) for a system were obtained by trial-error method.

Table 2. Control action equations

Control	Equation
Proportional (P) control	$P = K_c * e$
Integral (I) control	$P = \frac{1}{T_i} \int edt$
Proportional-Integral (P-I) control	$P = K_c(e + \frac{1}{T_R} \int edt)$

where,

P = change in controller output (KN/m^2)

K_c = controller gain (No dimension)
e = change in error (KN/m^2)
T_i = integral time (min)
T = time (min)
T_R = reset time (min)

* The unit usually depends on what controller is used. In pneumatic control, the unit should be pressure. In digital controller, the unit should be current.

2.4. Application of developed DO control system

Developed Proportional-Integral (P-I) DO control system was applied to an actual industrial wastewater treatability test using lab-scale sequencing batch reactor (SBR) system. Applied industrial wastewater has high COD concentration (Table 3) and was prone to foaming. Therefore, proper DO control was necessary to maintain aerobic condition and prevent unnecessary foaming from excessive aeration. Used wastewater characteristics were summarized in Table 3.

Table 3. Characteristics of industrial wastewater

Items*	Range	Average (number of samples)
pH	6.88 - 7.15	7.04 (88)
VSS	4 - 10	6 (88)
TSS	10 - 20	15 (88)
FCOD^1	3,270 - 9,800	6,699 (16)
TCOD^2	3,353 - 10,253	6,881 (16)

* : mg/L except pH
1 : Filtered COD
2 : Total COD

3. Results and Discussion

3.1. Proportional control

Based on Table 2, below equation 1 was developed for the proportional control experiment.

$$V = V_i + K_c{}^{*}\ (\text{DO set - DO measured}) \qquad (1)$$

where, V = output voltage (V)
V_i = initial applied voltage (Bias) (V)
K_c = proportional controller gain (No dimension)
DO set = dissolved oxygen set point (V)
DO measured = the current value from DO meter (V)

Weber (1973) reported the main advantage of proportional action as a control method is faster response than any other control action. The simple equation form Equation 1 makes the fast response possible. As shown in Equation 1, the proportional controller gain (K_c) is the primary variable affecting controller action. To evaluate proportional control for DO control in the bioreactor,

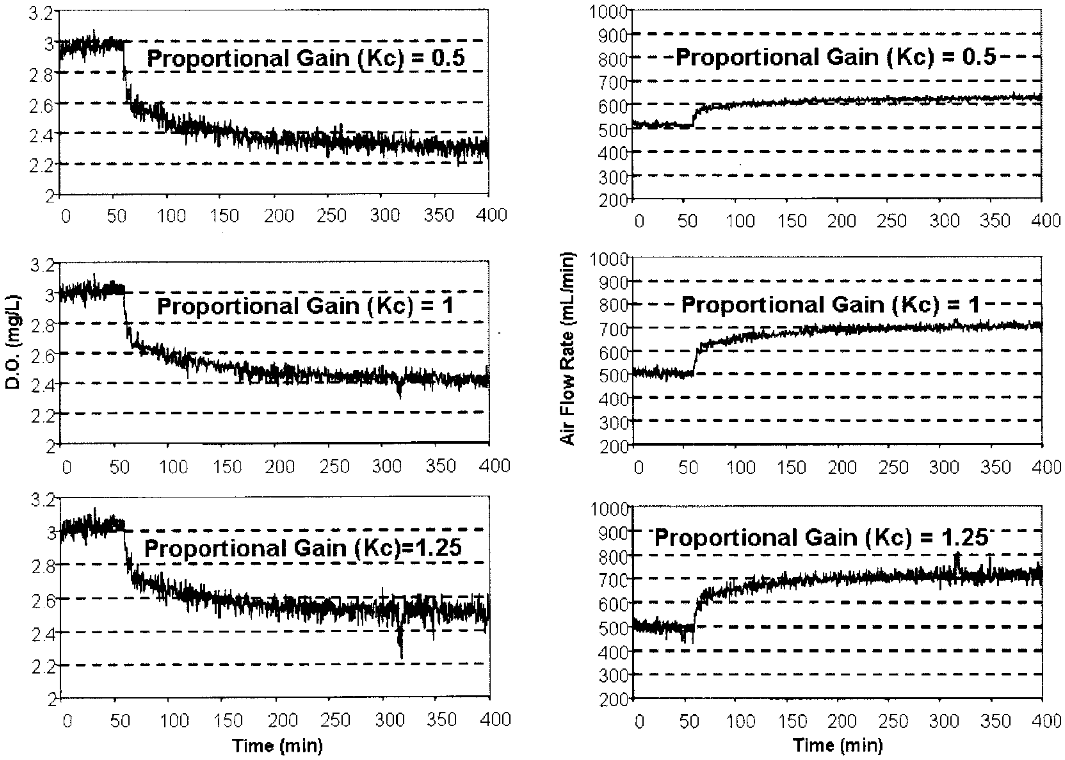

Fig. 2. DO concentration (Left) and corresponding air flow rate profiles (Right) under proportional control after a 1.5 step input in influent flow rate. (K_c values up: 0.5 V, middle: 1 V, down: 1.25 V)

experiments were conducted as a function of K_c. Three values were evaluated (0.5, 1, 1.25). Fig. 2 shows the time profiles of DO concentration and aeration pump flow rates before and after a 1.5 step input in influent flow rate was imposed. Before the step input was imposed, the bioreactor was maintained at a DO concentration of approximately 3 mg/L which was maintained by an initial voltage (bias) for the aeration pump.

However, after the flow rates increased, a DO concentration could not be raised up to 3 mg/L even though increased proportional controller gain (K_c) decreased offset, which is persistent error relative to the set-point. For processes controlled by proportional control, changes in operating condition lead to offset. The offset occurs because the controller can only proportionally correct for the error.

3.2. Integral control

Equation 2 was applied as control action during the integral control experiments.

$$V_1 = V_i + 1/T_i{*}(\text{DO set - DO measured}$$
$$V_2 = V_1 + 1/T_i{*}(\text{DO set - DO measured}) \qquad (2)$$

where, V_1 = previous output voltage (V)
V_2 = current output voltage (V)
V_i = initial voltage (Bias) (V)
T_i = integral time (No dimension)
DO set = dissolved oxygen set point. (V)
DO measured = the current value from DO meter (V)

As shown in Equation 2, the integral time (T_i) is the primary variable affecting controller action. To evaluate integral control for DO control in the bioreactor, experiments were conducted as a function of T_i. Each experiment was conducted using the experimental procedure outlined in the preceding section. The dissolved oxygen concentration and corresponding air flow rate profiles using integral control under different integral time are presented in Fig. 3.

Several characteristics of integral time (T_i) can be noted. As integral time (T_i) was lowered from 100 to 10, the control system tried to respond faster which caused the DO concentration to fluctuate faster around the set point. However, this response resulted in achieving the set-point faster as well. In the same figure, air flow rates for the integral control action experiments are presented.

First, the air flow rates are consistent with the DO profiles in that when DO was below the set-point, air flow rates increased proportionally. As expected, the rate of change in air flow rate was influenced by T_i with lower value of T_i resulting in sharper changes in air flow rates. Second, there was noise in the DO data but this noise was significantly reduced in the air flow rate response. The reduction in noise for the air flow rates is consistent with integral control which incorporates the history of control action to make adjustments, compared to proportional control which responses only to the current offset.

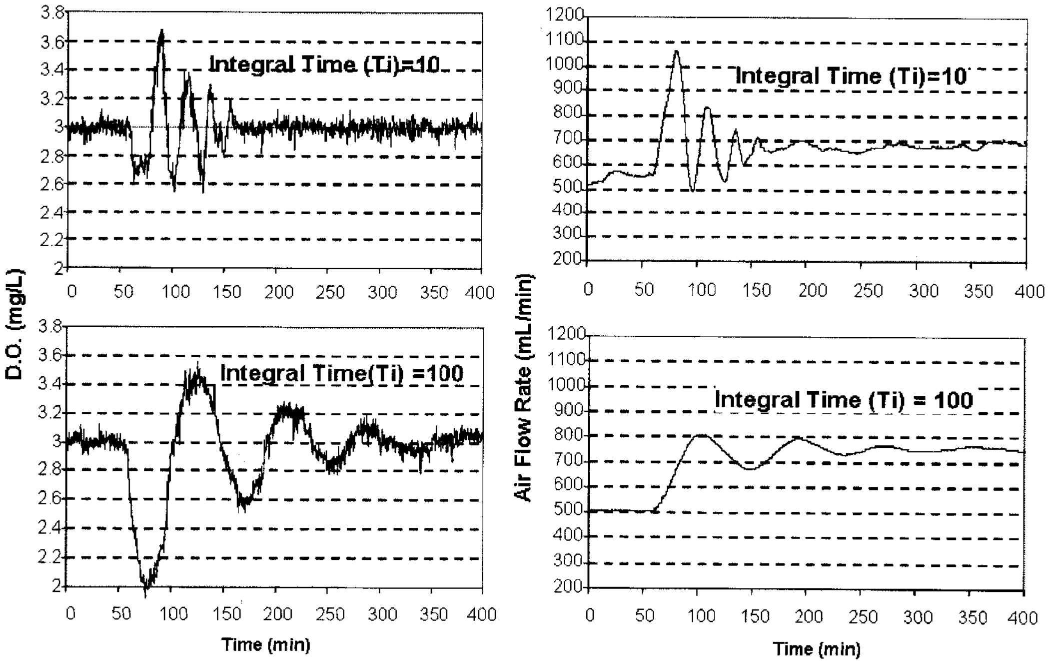

Fig. 3. DO concentration (Left) and corresponding air flow rate profiles (Right) under integral control after a 1.5 step input influent flow rate. (T_i values up: 10, down: 100).

3.3. Proportional-Integral control

Equation 3 was applied as control action during the proportional-integral control experiments.

$V_1 = V_i + K_c*(\text{DO set - DO measured}) + V_i$

$V_2 = V_i + K_c*(\text{DO set - DO measured}) + V_{ii}$

where, V_i, and V_{ii} are

$V_i \;=\; 1/T_i*(\text{DO set - DO measured})$

$V_{ii} \;=\; V_i + 1/T_i*(\text{DO set - DO measured}) \qquad (3)$

where, V_1 = previous output voltage (V)
V_2 = current output voltage (V)
V_i = initial voltage (Bias) (V)
K_c = proportional controller gain
T_i = integral time (No dimension)
DO set = dissolved oxygen set point (V)
DO measured = the current value from DO meter (V)

As shown in Equation 3, the proportional controller gain (K_c) and integral time (T_i) are the primary variables affecting controller action. One controller gain and one integral time were selected from previous experiments. The dissolved oxygen concentration and corresponding air flow rate profiles using P-I control are presented in Fig. 4. A proportional gain (K_c) of 1.25 and integral time (T_i) of 100 was employed.

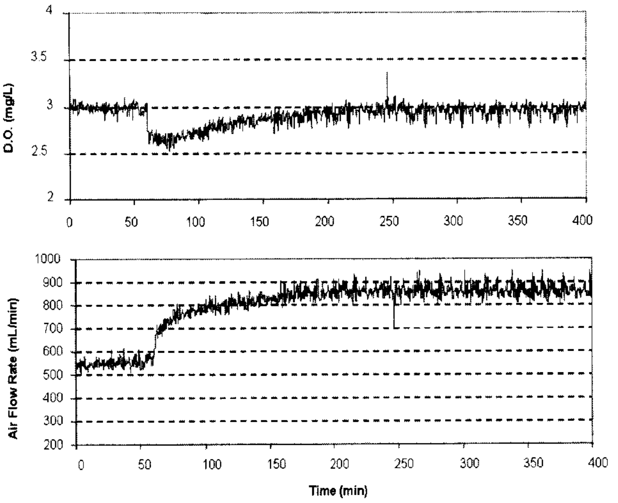

Fig. 4. DO concentration (Up) and corresponding air flow rate profiles (Down) under Proportional- Integral control after a 1.5 step input influent flow rate.

As shown in Figure 4, P-I control action was capable of maintaining the set-point of 3 mg/L before the step input of the feed. After the 1.5 fold increase was imposed, DO concentration dropped initially and then rebounded to the 3 mg/L set-point. The application of P-I control when compared to either P or I alone revealed several trends for the DO data. First, there was little if any offset in DO concentration after the system responded to the step input as compared to when P control was used. Second, the response was relatively fast with relatively little or no oscillation around set-point as observed in I control. Therefore, it is clear that the P-I control provides more stable control of DO as compared to either P or I control alone.

3.4. Application of developed DO control system

The SBR system employed was operated using sequencing periods of fill, react, settle, and decant. During the time of the DO data were collected, the period lengths were 8, 14, 1 and 1 hours for fill, react, settle and decant periods, respectively. Because of the high strength nature of the wastewater, feed was pumped into the SBR cyclically during the fill period using a 15 min on/15 min off pumping schedule. Accordingly, the feed period consisted of a series of step inputs to the SBR. Aeration of reactor contents was conducted during the fill and react periods. Two aeration pumps, a baseline and supplemental, were used in SBR operation because a single pump was not capable of supplying adequate dissolved oxygen. The airflow rate of the supplemental pump was controlled, while the airflow rate of the baseline pump was fixed at 1,400 mL/min. As a supplemental pump system, proportional and integral (P-I) control logic was employed in this experiment. In this experiment, (K_c) of 3 and integral time (T_i) of 100 was employed. Dissolved oxygen concentration data collected during the initial part of fill period of the SBR are presented in Fig. 5.

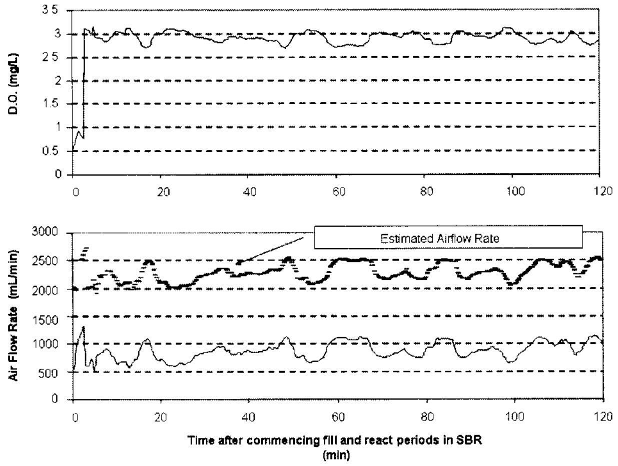

Fig. 5. DO concentration (Up) and corresponding air flow rate profiles (Down) under Proportional-Integral control during actual industrial wastewater treatability test.

As shown in Fig. 5 (up), a quick response to the DO set point was achieved after the aeration was initiated during the fill cycle. This quick response to the set-point is due to the controller gain used and because of the fixed base air flow rate employed. The bouncing DO profiles in Figure 5 are the result of the cyclic on-off wastewater input schedule. In Figure 5 (down), the lower line is the air flow rate controlled by P-I control action. The total flow rate (upper line) was estimated by adding the fixed air flow rate to the controlled air flow rate.

Dissolved oxygen control was employed in the SBR studies for approximately three months. During that time, this system was found to be capable of maintaining DO concentration from between 2.5 mg/L and 3 mg/L during the fill and react periods of SBR operation.

In this study, P-I-D (Proportional-Integral-Derivative) control, which might be one of the most popular control strategies, was reviewed but not conducted. Usually, the major advantage of P-I-D control over P-I control is getting the process stability (Weber 1973). However, as shown in Figure 4 and 5, applied P-I control for DO control showed stable performance in this system. Therefore, it was doubted if comparing DO and airflow rate profiles of P-I and P-I-D can characterize these two controls. However, P-I-D control should be considered if applied P-I control can not provide a stable performance.

4. Conclusions

The following conclusions were reached based on the results of this study.

1) An increase in proportional gain (K_c) resulted in reduced offset under proportional control.
2) An increase in integral time (T_i) resulted in a slower response in DO concentration with less oscillation, but took longer to get to the set point.
3) P-I control showed more stable and efficient control of DO and air flow rates compared to either proportional control or integral control.
4) The developed DO control system was able to control dissolved oxygen concentrations during the fill cycle of an SBR treating a high organic strength wastewater using P-I control.

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