CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761049

Control Strategy for Dissolved Oxygen of Paper Mill Activated Sludge Wastewater Treatment Process

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A fuzzy logic system combined with PID (Fuzzy-PID controller) to control the dissolved oxygen concentration in the paper mill wastewater treatment process is proposed based on the developed sequential batch reactor simulation model of the wastewater treatment process in paper mills. A case study with the presence of noise has been studied and evaluated with the criteria considered in Benchmark Simulation Model No. 1. The simulation results with white noise on the dissolved oxygen reveal that the Fuzzy-PID controller possesses better control indices than that of conventional PID controller. The good anti-interference ability of the Fuzzy-PID controller is meaningful and important for industrial application.

1. Introduction

An activated sludge wastewater treatment plant is regarded as a complex system due to its nonlinear dynamics, large uncertainty, multiple time scales in the internal process dynamics, and multivariable structure (Fajardo et al., 2016). The dissolved oxygen (DO) control method is the most widely spread in industrial process due to its significant influence on the behaviour and activity of the heterotrophic and autotrophic microorganisms living in the activated sludge (Olivieri et al., 2013). DO in the aerobic part of an activated sludge process needs sufficiently oxygen supply for the microorganisms, so that organic matter is degraded and ammonium is converted into nitrate. An excessively high level of DO, which requires high air flow rate, leads to a high-energy consumption and may cause the deterioration of sludge quality. The high DO in the internally recirculated water also makes the denitrification low efficient. For both economic and technical reasons, it is of important to control the DO level in the aerobic reactor.

For the DO control in the activated sludge wastewater treatment, most of the control strategies were based on the conventional PID control method (Yang et al., 2014). The control effect of the DO was sometimes dissatisfactory due to the limitation of the PID controller (Bahita and Belarbi, 2015). In this paper, a fuzzy logic system combined with the PID controller for the DO in the sequential batch reactor (SBR) is studied based on the SBR simulation model of the wastewater treatment process for paper mill in the previous work (Fenu et al., 2010). The new control strategy with on-line self-adjustment methods would adapt the changes of the activated sludge and optimize the wastewater treatment process. The criteria presented in the benchmark simulation model 1 (BSM1) is used for evaluating the accuracy of the control strategy.

2. Methods and models

As the basis of the control strategy for dissolved oxygen, simulation model should be set up firstly (Mohd and Aziz, 2016). Figure 1 shows the SBR wastewater treatment process of a paper mill. The influent is the mixture of paper mill wastewater and deinking wastewater. The developed model is based on a simplified version of Activated Sludge Model #1 (ASM1) of the International Water Association (IWA) (Henze et al., 2000). The ASM1 was chosen as the biological process model and the double-exponential settling velocity function was selected as a fair representation of the settling process.

Please cite this article as: Man Y., Shen W., Chen X., Pons M.-N., 2017, Control strategy for dissolved oxygen of paper mill activated sludge wastewater treatment process, Chemical Engineering Transactions, 61, 307-312 DOI:10.3303/CET1761049

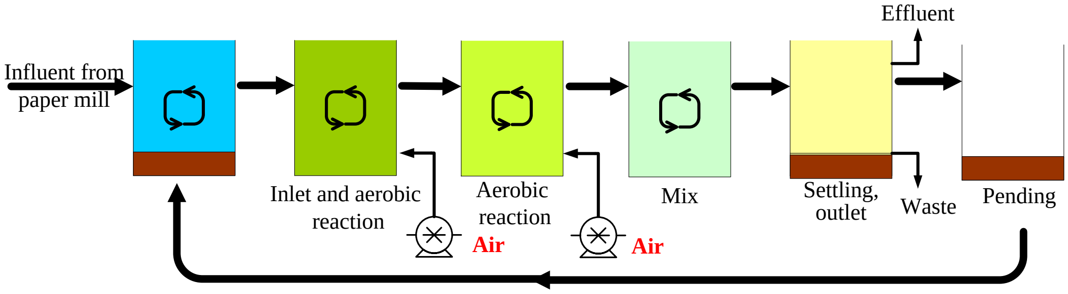


Figure 1: Schematic diagram of SBR wastewater treatment process for paper mill

2.1 Bioprocess model

ASM1 has become a reference for many scientific and practical projects and has been implemented in most of the available commercial software for modeling and simulating of activated wastewater treatment. Based on the ASM1, the SBR biological reactions part is first modeled, and the model is then modified and simplified according to the industrial SBR processes in a paper mill.

ASM1 has 13 components (state variables) and eight processes. However, for the limitation of the technological design of wastewater treatment, sensor technology and other factors, the whole ASM1 is rarely used directly for SBR modeling. The processes of the biological reactions are modified and simplified according to the industrial SBR process of the paper mill in this paper. The modification and simplification of ASM1 for bioprocess modeling is as follows. The SBR process of the paper mill does not contain anaerobic reaction, the anaerobic growth heterotrophic process and denitrification process could be neglected. In the SBR process, nutrient substances such as ceramide and phosphoric acid are added discontinuously to maintain the biological activity. The nitrogen and phosphorus in the wastewater treatment process are considered to be balanced as long as the nutrients nitrogen and phosphorus are added in the right amounts. To simplify the simulation model and make the model easier to be used in the industrial processes, nitrification and denitrification processes are neglected. This simplification has little impact on the aerobic growth heterotrophic process. Table 1 gives the matrix representation of the simplified ASM1 for the SBR process of the paper mill, which describes the components, process rate equations, and stoichiometry of the process. Nomenclatures in Table 1: S_I: the soluble inert organic matter (mg /L), S_S: the readily biodegradable substrate (mg /L), X_I: the particulate inert organic matter (mg /L), X_S: the slowly biodegradable substrate (mg /L), $X_{B,H}$: the active heterotrophic biomass (mg /L), X_P: the particulate products arising from biomass decay (mg /L), S_O: the dissolved oxygen concentration (mg /L), Y_H: the heterotrophic yield (mg X_{BH} COD formed/(mg COD utilized)), f_P: the fraction of biomass to particulate products, K_S: the half-saturation (heterotrophic growth) (mg /L), K_{OH}: the half-saturation (heterotrophic oxygen) (mg /L), μ_H: the maximum heterotrophic growth rate (/day).

Table 1: Matrix representation of the simplified ASM1 for paper mill SBR wastewater treatment process (Copp, 2002)

Component X_i	1	2	3	4	5	6	7	Process rate r_j
	S_I	S_S	X_I	X_S	$X_{B,H}$	X_P	S_O	[M/(L3 ×t)]
Aerobic growth Heterotrophic	-	$-\frac{1}{Y_H}$	-	-	1	-	$-\frac{1-Y_H}{Y_H}$	$\mu_H(\frac{S_S}{K_S+S_S})(\frac{S_O}{K_{OH}+S_O})X_{BH}$
Decay Heterotrophic	-	-	-	1- f_P	-1	f_P	-	$b_H X_{BH}$
Hydrolysis organic compounds	-	1		-1	-	-	-	$\frac{k_h X_S}{K_X+(X_S/X_{BH})}$

The general mass balance equations for the SBR bioprocess in a paper mill wastewater treatment process are as follows (Copp, 2002):

$$\frac{dV}{dt} = Q_{in} \quad (1)$$

$$\frac{dX_i}{dt} = \sum_{j=1}^{j=3} p_{i,j} \cdot r_j \cdot V + Q_{in} c_0 \quad (2)$$

where V is the volume of activated sludge and wastewater (m^3), Q_{in} is the influent flow rate (m^3/d), X_i is the weight of the i influent component (mg), $p_{i,j}$ is the j process of component X_i, r_j is the process rate, c_0 is the concentration of influent component (mg/L), and t is the time (h).

2.2 Modeling the settling process

The double-exponential settling velocity function of Takács et al. (1991) is selected to model the settling process:

$$v_s(X) = \max\{0, \min[v_0, v_0(e^{-r_k(X-X_{\min})} - e^{-r_p(X-X_{\min})})]\} \quad (3)$$

$$X_{\min} = f_{ns} X_f \quad (4)$$

where X, X_{min} and X_f are the total sludge concentration (mg/L), minimum attainable suspended solids concentration (mg/L) and mixed liquor suspended solids concentration (mg/L). The parameter f_{ns} is the non-settleable fraction, and r_p and r_h are the flocculants zone settling parameter (mg/L) and hindered zone settling parameter (mg/L). The parameters v_0, v_0' and v_s are the maximum settling velocity (m/d), maximum settling velocity (m/d) and settling velocity (m/d).
The reactor is modeled as a 10-layer non-reactive unit during the settling process. According to the above notations, the mass balances for the sludge are written as:

$$\frac{dX_m}{dt} = \frac{-\min(v_{s,m} X_m, v_{s,m} X_{m-1})}{h_m} \qquad (m = 10) \quad (5)$$

$$\frac{dX_m}{dt} = \frac{\min(v_{s,m} X_m, v_{s,m} X_{m+1})\text{-}\min(v_{s,m} X_m, v_{s,m} X_{m\text{-}1})}{h_m} \qquad (1 < m < 10) \quad (6)$$

$$\frac{dX_m}{dt} = \frac{\min(v_{s,m} X_m, v_{s,m} X_{m+1})}{h_m} \qquad (m=1) \quad (7)$$

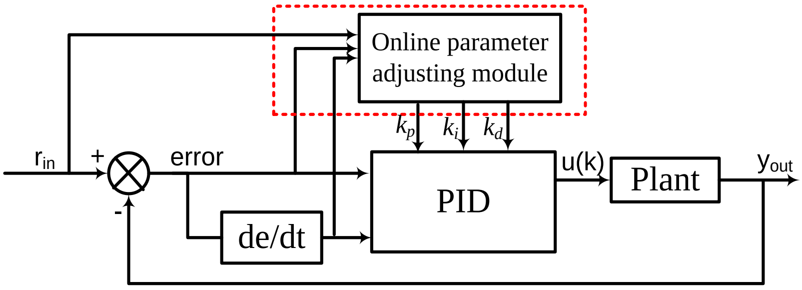
where X_m is the suspended solids concentration in the layer m (mg/L), $v_{s,m}$ is the settling velocity of the layer m (m/d), and h_m is the height of the layer m (m).
Based on the simplified ASM1 and the general equations for mass balance in the settling process, the SBR simulation model of paper mill wastewater treatment process is developed by MATLAB/Simulink 6.0. The schedule of the SBR process in the paper mill is shown in Table 2, and its common time is used for the default time of simulation (Kriš and Hadi, 2010).

Table 2: Schedule for the SBR process in the secondary fiber paper mill

Reaction phase	Common time (min)	Time range (min)
Inlet without aeration	60	30 - 90
Inlet with aeration	60	30 - 120
Aerobic reaction	120	60 - 180
Settling	60	40 - 90
Outlet	60	40 - 80
Total	360	-

3. Development of the adaptive controllers

The PID controller is chosen to maintain DO at a given level in most of the activated sludge wastewater treatment processes. Since the wastewater treatment process has serious time-varying characteristics, the fixed parameters of the PID controller are not suitable for the constantly fluctuant situation. One online PID parameter adjusting module is added to the conventional PID controller in this work. The structure of the improved PID controller is illustrated in Figure 2.



k_p: proportional coefficient; k_i: integral coefficient; k_d: differential coefficient

Figure 2: Schematic of the improved PID control system

As shown in Figure 2, r_{in} is the set point of DO (2 mg/L), y_{out} is the controlled DO variable, and *u(k)* is the flow rate of air (*KLa*) into the SBR process, which is the manipulated variable in the control system. The online parameter adjusting module was realized with fuzzy logic system combined with PID, which is used for controlling DO in the paper mill wastewater treatment process.

Fuzzy logic control has good performance in the control of the non-linear complicated systems (Mendes et al., 2014). In this study, a fuzzy logic system combined with the PID controller is used as an online PID parameter adjusting module to help the PID controller acquire appropriate parameters online.

Referred to Figure 2, the main task of the fuzzy-PID is to find the fuzzy relationships between the PID parameters and the DO error (*e*) and the change of DO error (*ec*), and to make the corresponding adjustments of the PID parameters online. *e* and *ec* are selected as the input fuzzy linguistic variables, and $\triangle k_p$, $\triangle k_i$ and $\triangle k_d$ are the output fuzzy linguistic variables. The fuzzy control rules in the study are given in Table 3, and the PID parameters are on-line adjusted via the rule weighing based on Table 3. Abbreviations in Table 3: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

Table 3: Fuzzy control rules of Δk_p, Δk_i, Δk_d

$\Delta k_p / \Delta k_i / \Delta k_d$		*ec*						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NS/NB/NS	PB/PB/PB	PB/PB/PB	PB/PB/PB	PB/PB/NB	PS/NS/NB	ZO/NM/NM
	NM	NM/NB/PM	PB/PB/PB	PB/PB/PB	PM/PM/PM	PM/PM/NM	ZO/NM/ZO	NS/NB/PS
	NS	NB/NB/PB	PB/PB/PB	PM/PM/PM	PM/PS/PM	PS/PS/NS	NS/NB/PM	NM/NB/PB
	ZO	ZO/ZO/ZO	ZO/ZO/ZO	ZO/ZO/ZO	ZO/ZO/ZO	ZO/ZO/ZO	ZO/ZO/ZO	ZO/ZO/ZO
	PS	PB/PB/PB	NB/NB/PB	NM/NB/PB	NS/NB/PM	PS/PS/NS	PM/PS/PM	PM/PM/PM
	PM	PB/PB/PB	NM/NB/PM	NS/NB/ZO	ZO/NM/ZO	PM/PM/NM	PB/PM/PM	PB/PB/PB
	PB	PB/PB/PB	NS/NB/NS	ZO/NM/NM	PS/NS/NB	PB/PB/NB	PB/PB/PB	PB/PB/PB

4. Controlling results and discussion

According to the proposed control strategies, the fuzzy-PID controller is applied to the simulated paper mill SBR wastewater treatment process. A case study with noise on DO sensors is conducted, and the performance of the controller is evaluated by Benchmark Simulation Model No. 1 (BSM1).

The noise and disturbance are objective existence in the process of the activated sludge wastewater treatment process. To perform an actual simulation, a white noise signal was added on the DO sensor. Figure 3 shows the controlling results of DO with white noise disturbance under the controlling actions of the different controllers. To observe the disturbing action, the variation of the measured DO with white noise is shown in Figure 3 (a).

In Figures 3(b) and 3(c), the values between two red dotted lines represent the errors between the maximum and minimum DO values. A smaller error indicates that a controller has a better capacity for resisting disturbance. The errors of the PID controller the Fuzzy-PID controller between the maximum and minimum DO are 0.20 mg/L and 0.14 mg/L. That means the Fuzzy-PID controller performs better than the conventional PID controller in the aspect of anti-interference. The rising time for the PID controller and the Fuzzy-PID controller during the control are 9.8 min and 14.5 min, which demonstrates the response of the Fuzzy-PID controller is slower than the PID controller. For the case with white noise, the Fuzzy-PID controller shows the better performance in the DO control.

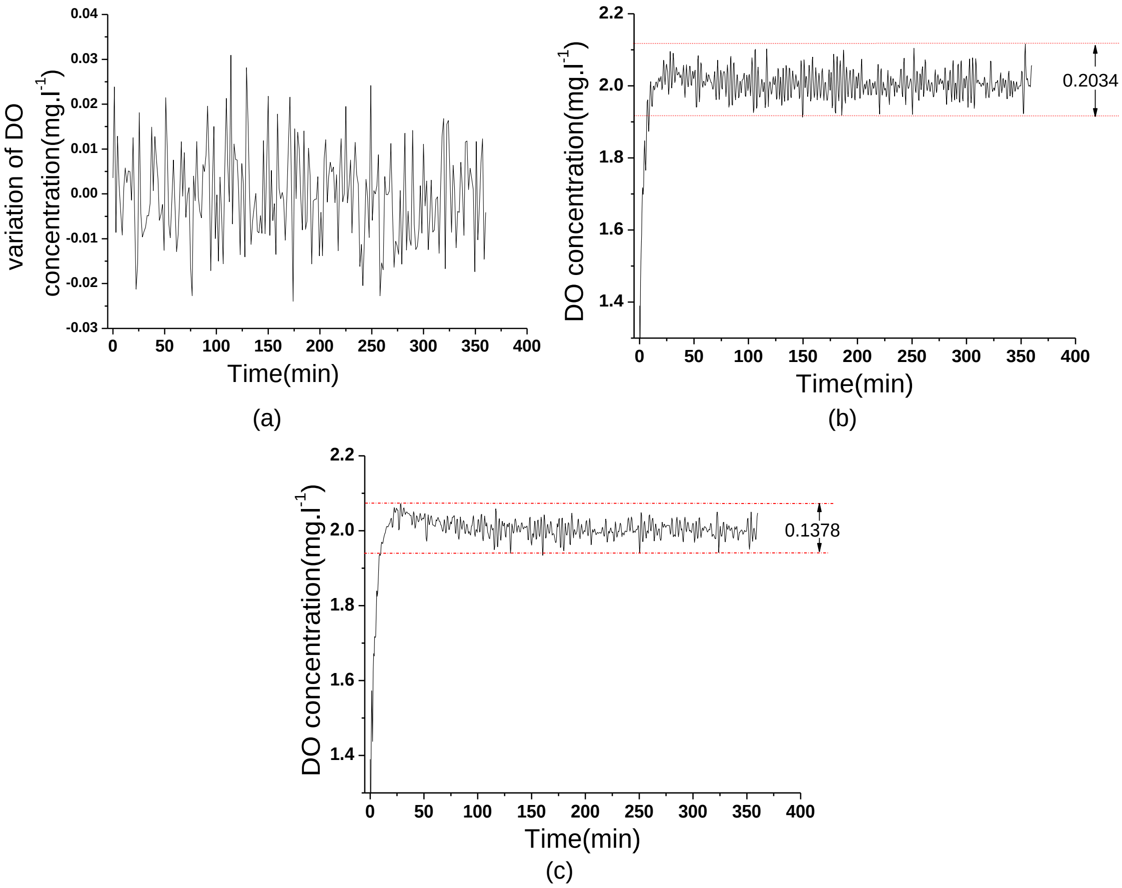


Figure 3: DO in the SBR reactor of the paper mill wastewater treatment process with different controllers (with white noise). (a) Variation of DO with white noise; (b) DO concentration of the paper mill wastewater with the conventional PID controllers; (c) DO concentration of the paper mill wastewater with the Fuzzy-PID controller.

Table 4: Comparison of performance indices with the PID controller and the Fuzzy-PID controller for DO in the SBR reactor of the paper mill wastewater treatment process

Item	Performance index	PID	Fuzzy-PID
Controlled variable	IAE	11.340	8.970
(DO, mg/L)	ISE	1.280	1.377
	DEV^{max}	0.116	0.072
	VAR(e)	0.003	0.003
Manipulated variable	DEV^{mv}	2.588	2.397
(KLa, h)	$DEV^{\triangle u}$	0.555	0.297
	VAR($\triangle u$)	0.012	0.003

According to BSM1, a group of performance assessment indices is suggested to evaluate the controller performance. It contains two parts: the controlled variable: IAE (integral of absolute error), ISE (integral of square error), DEV^{max} (maximal deviation from set point) and VAR(e) (error variance); and the manipulated variable: DEV^{mv} (range), $DEV^{\Delta u}$ (maximum deviation in the change in manipulated variable), VAR (Δu) (variance of manipulated variable variations). These indices serve as a proof that the proposed control strategies are (or are not) applied properly. The above indices with the PID controller and the Fuzzy-PID controller for the DO control in the SBR reactor of the paper mill wastewater treatment process are summarized in Table 4. Compared with PID controller, with the presence of noise, almost all of the assessment indices of the controlled variable and the manipulated variable with the Fuzzy-PID controller are smaller, which means that it achieves better controlling performance than that of PID controller. Since the disturbance of noise are ubiquitous in the field, these improved indices of the Fuzzy-PID controller in Table 4 manifest its good anti-interference ability, which is meaningful and important in the industrial application.

5. Conclusions

Based on the developed SBR simulation model of the wastewater treatment process for paper mill in our previous work, a Fuzzy-PID control strategy for the DO control in the SBR process have been studied and evaluated using the criteria considered in BSM1 by a case study. Simulation results with noise reveal that the Fuzzy-PID controller achieves the better controlled and manipulated indices than that of PID controller, where some of the controlling indices are improved, which demonstrates the Fuzzy-PID controller's good ability for anti-interference. Although the Fuzzy-PID controller does not demonstrate good performance in the response rate, it could be applied to improve the control precision.

Acknowledgments

The research was supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20130172110014), Research Funds of State Key Laboratory of Pulp and Paper Engineering, South China University of Technology (No. 2017ZD03 and No. 2015C05), Science and Technology Planning Project of Guangdong, China (No. 2015A020215012), National Natural Science Foundation of Guangdong, China (No. 2016A030313478), and Science and Technology Program of Guangzhou, China (No. 201607010050).

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