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A SYSTEM FOR DISSOLVED OXYGEN CONTROL IN INDUSTRIAL AERATION TANK

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Abstract. The control system is developed for accurate set-point control of dissolved oxygen concentration in industrial aeration tank based on adaptation of PI controller to time-varying dynamics of the controlled process. The controller adaptation algorithm refers to the process state model-based transfer function that follows changes in process dynamics by updating the function parameters with on-line measurements of process variables, and the controller tuning rules developed for typical structure transfer function models.

The control system was investigated via computer simulation of the dissolved oxygen concentration set-point control in an industrial aeration tank under process disturbances and set-point step changes. The control system demonstrates fast adaptation of PI controller parameters and noticeably higher accuracy control compared to that of ordinary fixed gain PI controller.

Keywords: mathematical model; adaptive control; dissolved oxygen concentration; wastewater treatment process.

1. Introduction

One of the key technological factors of the activated sludge treatment process in aeration tanks is oxygen supply, and the oxygen supply rate is the main parameter actively affecting biological treatment process. Basic requirement for oxygen supply is that the dissolved oxygen concentration (DOC) in nitrification zone is not less than predetermined level (2 kg m^{-3}) [1]. If the nitrification and denitrification processes take place in the same aeration tank, the energy saving and maintenance balance between aerobic / anoxic sections of the sludge flocks can be achieved by accurate control of DOC for keeping the optimal technological regime, usually 0,15-0,5 kg m^{-3} [1]. As the controlled process is highly nonlinear and nonstationary, an ordinary PID control is not adequate to cope with the DOC accurate control task. The DOC control problem in industrial aeration tank is illustrated by a graph in Figure 1, which shows the performance of ordinary PID controller by tracking the DOC set-point at process state change.

Various adaptive and nonlinear control approaches have been proposed for controlling DOC in aerotanks under time-varying operating conditions. Turmel *et al.* [2] investigated several control methods (PID, fuzzy logic and self-tuning control) by computer simulation of the activated sludge plant using the Activated Sludge Model 1 (ASM1). The self-tuning controller based on generalized predictive control method demonstrated robust behaviour and proper responses to various operating conditions. There was indicated a problem of reliable measurements, which can be used to implement the control system. Galluzzo *et al.* [3] proposed an expert control structure for controlling the DOC, which takes into account several processes

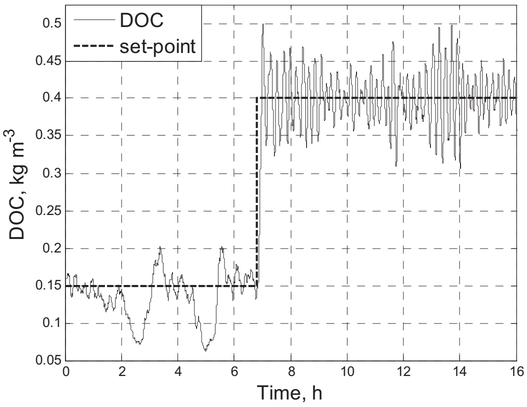

Figure 1. Illustration of DOC control in industrial aeration tank by ordinary PID controller

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that are influenced by oxygen concentration in aerator. In the control system, a supervisory fuzzy controller determines the DOC set-point for inner control loop, in which an adaptive robust generic model control is used. Tzoneva [4] presented an approach of periodic retuning of DOC controller that does not require disturbing of technological process. Identification of process dynamic parameters is performed on personal computer with the Matlab/Simulink environment, connected to PLC. De Leon *et al.* [5] proposed two dimensionless parameters, which relate the physiological, operational and bioreactor design parameters with the tuning parameters of PID control algorithm. The dimensionless parameters can be incorporated into adaptive control strategy without disturbing the ongoing process. Chang Kyoo Yoo *et al.* [6] used the Kalman filter to estimate two important parameters that characterize dynamics of the biological treatment process – oxygen transfer rate and respiration rate. These parameters were further applied for nonlinear model-based control of DOC. Caraman *et al.* [7] proposed a predictive controller of DOC with a neural network as internal model of the controlled process. The similar approach is used by Holenda *et al.* [8], only the ASM1 model is used for the process modeling.

In the presented paper, an adaptive control system of DOC in industrial aeration tank is proposed, in which *a priori* knowledge of the controlled process and available on-line measurements of process variables are exploited. The process knowledge is included in a simple model, which is updated with on-line measurements of process variables and applied for permanent retuning of controller parameters. Advantage of the proposed control system is fast adaptation of controller to operating conditions and avoidance of process disturbances for the dynamic parameters estimation.

2. Aero-tank process

Technological scheme of the wastewater treatment process is shown in Figure 2.

Incoming wastewater flow F_{inlet} through the screens, comminutor and grit chamber falls into the distribution chamber, in which the wastewater is mixed with the returned sludge flowing in at rate F_{ret}. The mixed wastewater flow F_{bio} falls into aeration (biological treatment) tank. In the aeration tank, the wastewater to be purified is brought into contact with the active sludge mass. Oxygen required for the biological process is supplied to aeration tank through the air blowing equipment. The airflow u for aeration comes from the blower station. The mixing system provides with the best possible contact between the bacteria cells and the nutrient, the widespread diffusion of oxygen to those areas requiring oxygen, and prevents formation of deposits. The purified water falls into final settling tank, in which the water is separated from the microorganisms' culture. The biological sludge collected from the settling tank is returned to the aeration tank. The excessive sludge with the flow rate F_{exc} is removed for digestion.

The most important technological parameter actively affecting biological treatment process is DOC, which is controlled by manipulating the air supply rate. To ensure the most effective biotechnological regime, the DOC in aeration tank is to be accurately controlled at predetermined optimal level. Importance of the DOC accurate control is also related to significant energy expenses for aeration.

The main problem that complicates accurate set-point control of DOC is variation of the controlled process dynamics caused mainly by unpredictable changes of oxygen uptake rate as well the flow rate of incoming wastewater and DOC concentration in incoming wastewater.

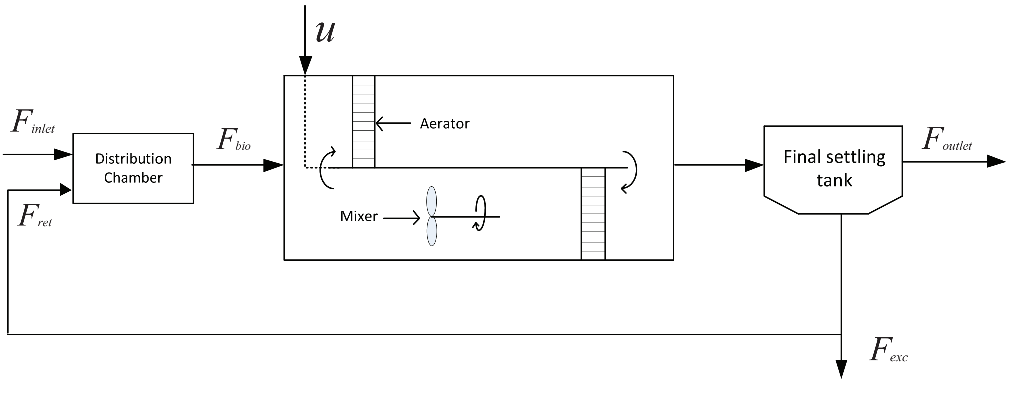


Figure 2. Technological scheme of the wastewater treatment process

3. Development of control system

The approach to the process controller adaptation is based on using in the DOC control system an adaptive transfer function model for tracking time-varying dynamical parameters of process and permanent retuning of the feed-back controller parameters [9].

Development of the transfer function model refers to a first principles model describing the mass balance for DOC in aeration tank:

$$\frac{dc}{dt}=K_L a\cdot(c^*-c)+(c_{in}-c)\frac{F_{bio}}{V}-OUR, \quad (1)$$

$$K_L a=\alpha\cdot u^{\gamma}, \quad (2)$$

where c is the DOC (control variable), kg m^{-3}; c^* - is saturation value of DOC, kg m^{-3}; $K_L a$ is volumetric oxygen transfer coefficient from gas to liquid phase, h^{-1}; c_{in} is DOC in the inlet wastewater, kg m^{-3}; F_{bio} is the inlet flow rate of wastewater, m^{3}h^{-1}, V is volume of aeration tank, m^3, OUR is oxygen uptake rate, kg m^{-3} h^{-1}; u is air flow rate (manipulated variable), m^{3}h^{-1}; α, γ are the model parameters.

Time-varying dynamics of the controlled process in the vicinity of operating point can be described by linear equation (3) derived by linearization of the equation (1) with respect to variables c and u around the process state point at time t_k :

$$\frac{d\Delta c}{dt}=-\frac{1}{T(t_k)}\cdot\Delta c+\frac{K(t_k)}{T(t_k)}\cdot\Delta u, \quad (3)$$

or by a 1st order transfer function model:

$$G_{\Delta c/\Delta u}(s)=\frac{\Delta c(s)}{\Delta u(s)}=\frac{K(t_k)}{T(t_k)s+1}, \quad (4)$$

$$K(t_k)=\left[\frac{\gamma\alpha u^{\gamma}(c^*-c)V}{u(\alpha u^{\gamma}V+F_{bio})}\right]_{|t=t_k}, \quad (5)$$

$$T(t_k)=\left[\frac{V}{\alpha u^{\gamma}V+F_{bio}}\right]_{|t=t_k}, \quad (6)$$

where s is the Laplace operator; Δc, Δu are small deviations of c and u form the current state point; $\Delta c(s)$, $\Delta u(s)$ are the Laplace transforms of Δc and Δu, $K(t_k)$, $T(t_k)$ are process gain coefficient and time constant at time point t_k, respectively.

The parameters α, γ, c^* that define oxygen transfer conditions in aeration tank can vary with the time-varying state of aeration tank process, therefore, estimation of the dynamic parameters K and T by formulas (5), (6) with predetermined parameter values does not ensure the desirable accuracy. The dynamic parameter estimation can be improved at quasi-steady state conditions with respect to DOC ($dc/dt\approx 0$) by using estimated values of the OUR . At the steady state conditions, the oxygen transfer rate term $K_L a(c^*-c)$ can be estimated from the equation (1) and the F_{bio}, c_{in} and OUR measurements:

$$K_L a(c^*-c)V=OUR_t-F_{bio}(c_{in}-c), \quad (7)$$

where OUR_V is total oxygen uptake rate ($OUR_V=V\cdot OUR$).

Taking into account the relationship (7), the dynamic parameters K and T can be estimated from the following relationships:

$$K(t_k)=\left[\frac{\gamma(c^*-c)\left(OUR_t-F_{bio}(c_{in}-c)\right)}{u\left(OUR_t+F_{bio}(c^*-c_{in})\right)}\right]_{|t=t_k} \quad (8)$$

$$T(t_k)=\left[\frac{V(c^*-c)}{OUR_t+F_{bio}(c^*-c_{in})}\right]_{|t=t_k}. \quad (9)$$

By updating the transfer function model (4), (8), (9) with the control variable value $u(t_k)$, the set-point value for DOC ($c(t_k)=c_{set}(t_k)$), the measured values $F_{bio}(t_k)$, $c_{in}(t_k)$ and the estimated value $OUR_V(t_k)$, the model (4) follows variations of the process dynamics under real-time operating conditions.

For tuning the feed-back controller, along with the time-varying dynamics described by the model (4), (8), (6), the time-invariant dynamics of the DOC electrode and the air blowing machines, as well the air flow rate-dependent transport delay are taken into account. Assuming that dynamics of the DOC electrode and the blowing machines can be described by first order plus time delay models, the resultant transfer function of the controlled process is as follows:

$$G^*_{\Delta c/\Delta u}(s)=\frac{K(t_k)}{T(t_k)s+1}\cdot\frac{1}{\mathrm{T_e}s+1}\cdot\frac{1}{\mathrm{T_{bm}}s+1}e^{-s[\tau_p(t_k)+\tau_{\mathrm{m}}]}, \quad (10)$$

$$\tau_p(t_k)=\mathrm{V_p}/u(t_k), \quad (11)$$

where T_e, T_{bm} are time constants of the DOC electrode and the blowing machine, respectively, h; τ_p, τ_{bm} are time delays of the air flow and the blowing machines, respectively, h; V_p is volume of the air supply pipeline, m^3.

In order to apply for controller adaptation the tuning rules developed for first order plus time delay (FOPTD) models [10], the transfer function (10) is further reduced on-line to the FOPTD model:

$$G_{pr}(s)=\frac{K_{pr}(t_k)}{T_{pr}(t_k)s+1}\exp\left(-\tau_{pr}(t_k)\right), \quad (12)$$

where $K_{pr}(t_k)$, $T_{pr}(t_k)$ and $\tau_{pr}(t_k)$ are resultant gain, time constant and resultant time delay of the controlled process at time t_k, respectively. The model parameters $T_{pr}(t_k)$ and $\tau_{pr}(t_k)$ are updated by fitting the FOPTD model (12) to the simulated step response of the transfer function (10) at each sampling time. The Smith‘s approximation [10] is applied for fitting the FOPTD model.

Taking into account noticeable process noise influencing the feed-back signal from the DOC electrode, we use in the control system the PI controller (instead of PID) that is less sensitive to input signal noise. The velocity form of modified discrete PI control algorithm is

$$u(t_k)=u(t_{k-1})+Du(t_k), \quad (13)$$

$$e(t_k)=c_{set}(t_k)-c(t_k), \quad (15)$$

$$\begin{aligned}Du(t_k)&=K\ (t_k)\{[b(t_k)c_{set}(t_k)-c(t_k)]-\\&-[b(t_k)c_{set}(t_{k-1})-c(t_{k-1})]+\\&+\frac{\Delta t}{T_i(t_k)}e(t_k)\Bigg\}, \quad (14)\end{aligned}$$

$$e(t_k)=c_{set}(t_k)-c(t_k), \quad (15)$$

where Du is increment/decrement of air flow rate, $m^3\ h^{-1}$; K_c is controller gain coefficient, $m^3 h^1/ kg\ m^3$; T_i is controller integration constant, h; b is set-point weighting; Δt is time discretization step of control action, h; c is measured value of DOC, $kg\ m^{-3}$.

The controller parameters $K_c(t_i)$, $T_i(t_i)$, $b(t_i)$ are recalculated at each sampling instant using updated values of the FOPTD model (12) parameters $K_{\Delta c/\Delta u}(t_k)$, $T_{pr}(t_k)$, $\tau_{pr}(t_k)$ and the Kappa-Tau tuning rules for maximum sensitivity $M_s=2.0$ developed for the FOPTD model [11]:

$$\begin{aligned}K_c&=0.78\frac{T_{pr}(t_k)}{K_{pr}(t_k)\tau_{pr}(t_k)}\cdot\\&\cdot\exp\left(-4.1\cdot\tau(t_k)+5.7(\tau(t_k))^2\right), \quad (16)\end{aligned}$$

$$\begin{aligned}T_i(t_k)&=0.79\cdot T_{pr}(t_k)\cdot\\&\cdot\exp\left(-1.4\cdot(t_k)+2.4(\tau(t_k))^2\right), \quad (17)\end{aligned}$$

$$\begin{aligned}b(t_k)&=0.44\cdot\exp\big(0.78\cdot\tau(t_k)-\\&-0{,}45(\tau(t_k))^2\big), \quad (18)\end{aligned}$$

$$\tau(t_k)\frac{\tau_{pr}(t_k)}{\tau_{pr}(t_k)+T_{pr}(t_k)}. \quad (19)$$

The structure of the DOC adaptive control system is presented in Figure 3.

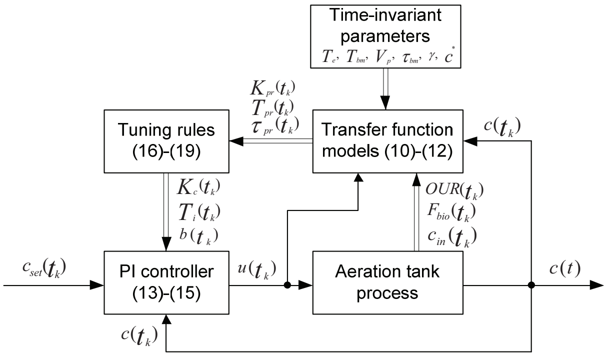


Figure 3. Block-scheme of the adaptive control system

In the adaptation algorithm, the control action, calculated at time point t_k for sampling interval $t_k \le t < t_{k+1}$ refers to the process state at time t_k. Preliminary tests of the adaptive control system have shown that the system performs well if there is no significant change of process state during the sampling interval. Although the changes of process state variables are relatively slow, the above condition is often violated by the control action itself as the process gain depends on the control variable value (equation (8)). Under significant changes of control action in consecutive sampling intervals the calculated value of control variable is actually different from the optimal one, if estimation of process dynamic parameters in the controller adaptation algorithm refers to a previous value of control variable. The above problem is solved by estimation of process dynamic parameters with respect to a mean value of the previous control action (u_{k-1}) and the intended action (u_k). This computation problem is solved at each sampling time by using the iterative procedure presented in Figure 4.

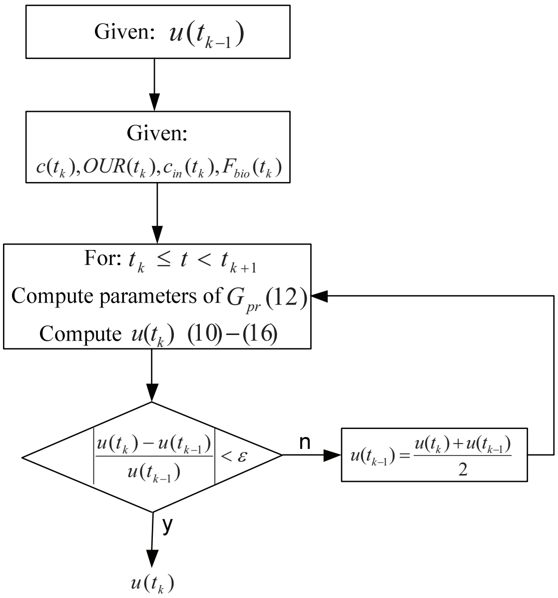


Figure 4. Flowchart of computation algorithm

4. Simulation of the control system performance

Performance of the control system (Figure 3) has been investigated via computer simulation, using Matlab/Simulink tools. In the simulation experiments, the controlled process was modeled by equations (1)-(2) and the first order dynamic models of the control system elements: the DOC electrode and the air blowing machines. The delay of control action (aeration rate) due to air flow transportation time that depends on the air flow rate is also taken into account. The model parameter values and initial values of process variables applied in the simulation experiment are given in Table 1 [12].

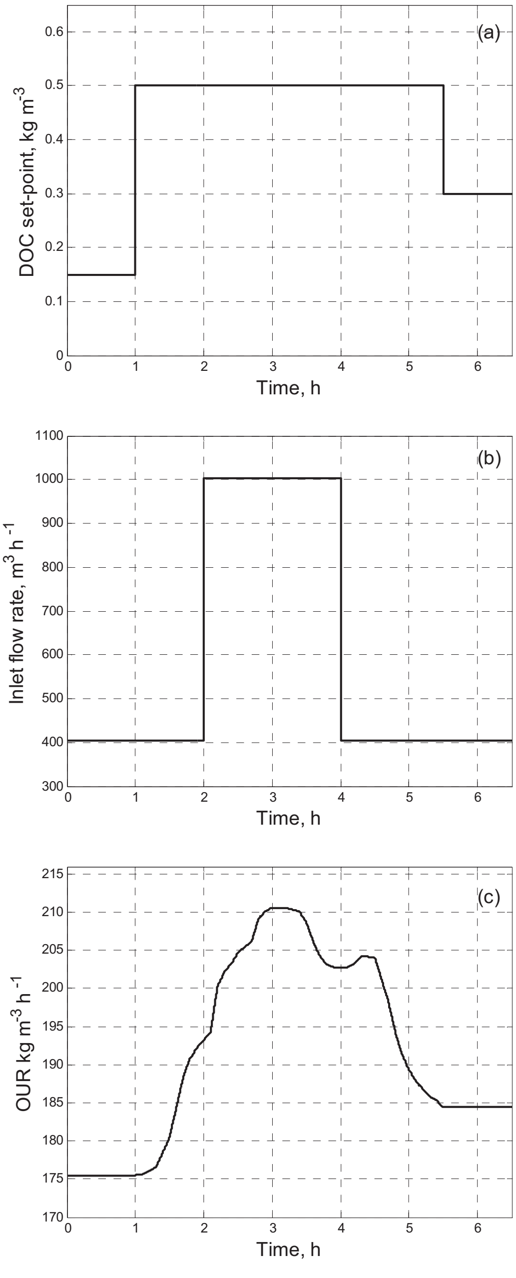
Table 1. Model parameters and initial values of process variables

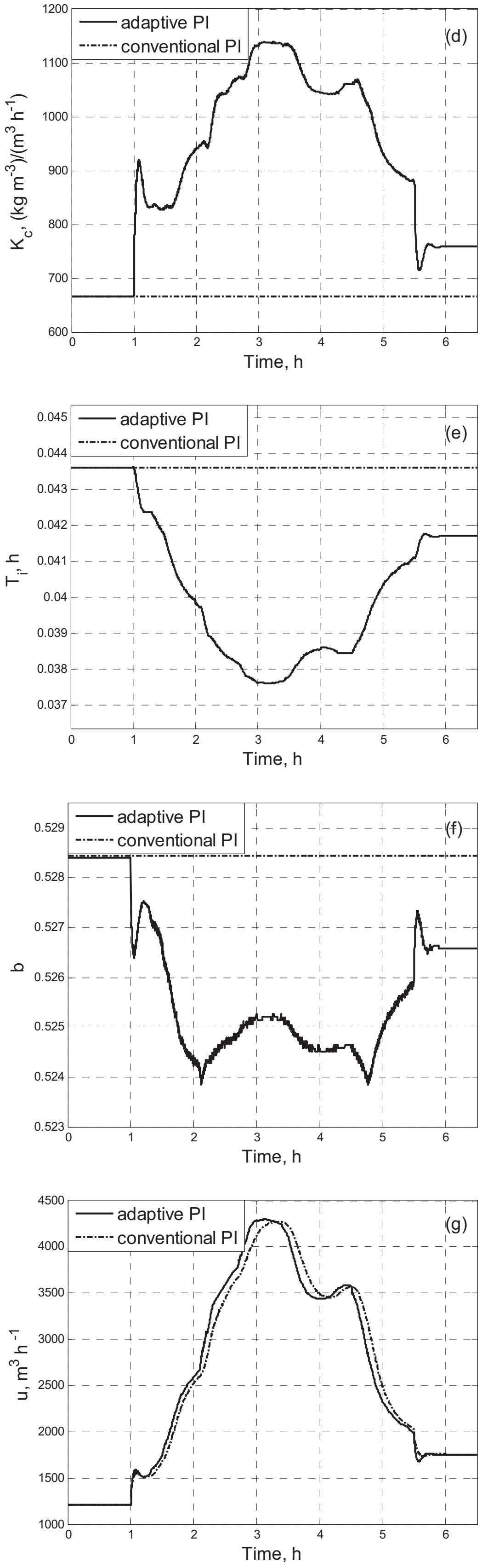
Values of model parameters		Initial values of process variables
$c_{in} = 6$ kg m^{-3},	$V_p = 3.31$ m^3	$c = 0.15$ kg m^{-3}
$c^* = 10$ kg m^{-3},	$\alpha = 5.09$	$u_{set} = 1197$ m^{3}h^{-1}
$T_{bm} = 3.33\cdot10^{-3}$ h,	$\gamma = 0.138$	$OUR = 175$ kg m^{-3}h^{-1}
$T_e = 2.22\cdot10^{-2}$ h,	$\tau_{bm} = 1.11\cdot10^{-3}$ h	$F_{bio} = 403$ m^{3}h^{-1}

The changes in process dynamics were simulated by varying the oxygen uptake rate (OUR) and the inlet flow rate of wastewater (F_{bio}). In the control algorithm (10)-(12), the sampling time $\Delta t = 0.01$ h was used.

Responses of the adaptive control system to the DOC set-point step changes under the OUR and the wastewater flow-rate disturbances are presented in Figure 5. The set-point and the disturbance time-profiles are shown in Figures 5(a)-(c), respectively. Variation of the OUR presented in Figure 5 (c) is estimated from the real process observation data. Adaptation of the adaptive PI controller parameters K_c, T_i and b is illustrated in Figures 5(d)-(f), respectively. Variation of the manipulated variable u is shown in Figure 5(g). Responses of the controlled DOC by tracking the set-point changes and compensation the disturbances are presented in Figure 5(h).

For comparison, responses of the conventional PI control system with the fixed parameters of controller ($K_c = 665.8$, kg m^{-3}/m^3 h^{-1}; $T_i = 0.0437$, h; $b = 0.5284$) adjusted for initial values of technological parameters at the simulation experiment are shown in Figures 5(d)-(h) by dotted lines.





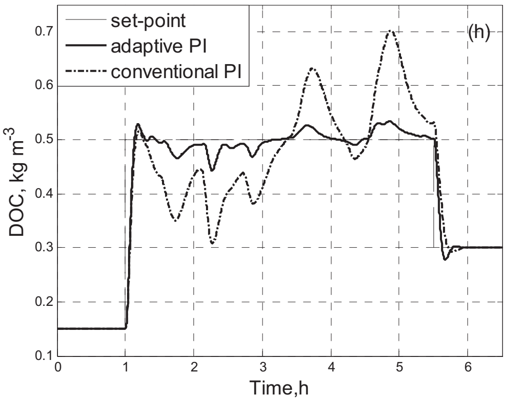


Figure 5. Performance of the control system at the OUR and the inlet flow rate disturbances and the controlled DOC set point changes

The simulation results demonstrate fast adaptation of controller parameters and noticable improvement of the DOC control accuracy by tracking set-point with the adaptive controller compared to that of conventional PI controller.

5. Conclusions

An adaptive control system is developed for set-point control of dissolved oxygen concentration at wastewater treatment process. Adaptation of process controller to time-varying operating conditions is based on the process state model-based transfer function, which follows the process dynamics changes by updating it with the on-line measurements of process variables. The adaptive transfer function is applied in the control system for permanent retuning of PI controller parameters.

Performance of the control system is investigated by computer simulation of the DOC set-point control under process disturbances: oxygen uptake rate and inlet wastewater variations, and the set-point step changes. Simulation results demonstrate fast adaptation of controller and significant improvement in set-point tracking accuracy compared to that with ordinary PI controller.

References

[1] **Wang L. K., Shammas N. K., Hung Y. T.** Advanced biological treatment processes. Handbook of environmental engineering, Vol.9. 2009. 15,185-208.

[2] **Turmel V. J., Williams D., Jones K. O.** Dissolved oxygen control strategy for an activated sludge process. UKACC international conference on CONTROL '98, conference publication No. 455, 1998

[3] **Galluzzo M., Ducato R., Bartolozzi V., Picciotto A.** Expert control of DO in the aerobic reactor of an activated sludge process. *Computers and Chemical Engineering 25*, 2001. 619-625.

[4] **Tzoneva R.** Optimal PID control of the dissolved oxygen concentration in the wastewater treatment plant. *Proceedings of 8^{th} IEEE Africon Conference*, 2007. 1116-1121.

[5] **De Leon A., Barba-de la Rosa A.P., Mayani H., Galindo E., Ramirez O. T.** Two useful dimensionless parameters that combine physiological, operational and bioreactor design parameters for improved control of dissolved oxygen. *Biotechnology Letters* 23, 2001. 1051-1056.

[6] **Chang Kyoo Yoo, Jong-Min Lee, In-Beum Lee.** Nonlinear model-based dissolved oxygen control in a biological wastewater treatment process. *Korean J. Chem. Eng., 21(1)*, 2004. 14-19.

[7] **Caraman S., Sbarciog M., Barbu M.** Predictive control of a wastewater treatment process. *International Journal of Computers, Communications & Control Vol. II (2007), No.2*, 132-142.

[8] **Holenda B., Domokos E., Redey A., Fazakas J.** Dissolved oxygen control of the activated sludge wastewater treatment process using model predictive control. *Computers and Chemical Engineering 32*, 2008. 1270-1278.

[9] **Brazauskas, K., Levišauskas, D.** Adaptive transfer function-based control of nonlinear process. Case study: Control of temperature in industrial methane-tank // International Journal of Adaptive Control and Signal Processing. Wiley InterScience, 2007, Vol. 21 , p. 871-884.

[10] **Smith C.A, Corripio A.B.** Principles and Practice of Automatic Process Control. 3rd ed. Hoboken [N.J.]: John Wiley & Sons, 2006. 563p.

[11] **Astrom, K.J., Hagglund, T.** PID control – Theory, Design and Tuning. Instrument Society of America, Research Triangle Park, NC, 2nd ed., 1995.

[12] **Jonelis K., Levišauskas D., Brazauskas K.** Mathematical model for adaptive control of dissolved oxygen concentration in biological wastewater treatment process, Electrical and control technologies. ISSN 1822-5934, 2009, pp.121-124.

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