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Design of a modern automatic control system for the activated sludge process in wastewater treatment

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ABSTRACT

The Activated Sludge Process (ASP) exhibits highly nonlinear properties. The design of an automatic control system that is robust against disturbance of inlet wastewater flow rate and has short process settling times is a challenging matter. The proposed control method is an I-P modified controller automatic control system with state variable feedback and control canonical form simulation diagram for the process. A more stable response is achieved with this type of modern control. Settling times of 0.48 days are achieved for the concentration of microorganisms, (reference value step increase of 50 $mg\cdot L^{-1}$) and 0.01 days for the concentration of oxygen (reference value step increase of 0.1 $mg\cdot L^{-1}$). Fluctuations of concentrations of oxygen and microorganisms after an inlet disturbance of $5\times10^3 m^3\cdot d^{-1}$ are small. Changes in the reference values of oxygen and microorganisms (increases by 10%, 20% and 30%) show satisfactory response of the system in all cases. Changes in the value of inlet wastewater flow rate disturbance (increases by 10%, 25%, 50% and 100%) are stabilized by the control system in short time. Maximum percent overshoot is also taken in consideration in all cases and the largest value is 25% which is acceptable. The proposed method with I-P controller is better for disturbance rejection and process settling times compared to the same method using PI controller. This method can substitute optimal control systems in ASP.

1. Introduction

Activated Sludge Process (ASP) is a biological process commonly used during wastewater treatment where microorganisms convert organic substances (substrate) to CO_2 and H_2O *via* aerobic respiration as shown in reference [1]. In its simplest form, ASP is consisted of an aerobic bioreactor (or aeration tank), where microorganisms participate in metabolic reactions degrading organic compounds, and a clarifier (or settler) where microorganisms are separated from treated wastewater *via* gravity. Treated wastewater is discharged from the upper part of the clarifier, whereas settled biological sludge is partly recycled from the settler to the bioreactor to maintain stable concentration of microorganisms and is partly wasted from the system for further treatment as shown by [2] and (Fig. 1).

It is widely known that Wastewater Treatment Plants (WWTPs) often receive wastewater that presents significant daily and seasonal variations in influent flow rates. These variations may have negative effects on ASP performance and in some cases may result in process failure [1]. Because of that, an advanced control system is necessary to make the process more robust in such variations, improving in parallel process' settling time.

So far, the majority of the systems that have been used to control ASP are based on P or PI controllers (classical automatic control) as shown by [3,4]. Sometimes even PID controllers are used. Classical controller parameters' adjustment is done through compensation procedures using root locus and frequency response (if the process' model is known) or through Ziegler–Nichols method which requires termination of the system function until the adjustment is completed [5]. In cases that only one ASP unit is available in a WWTP, the environmental pollution during parameter adjustment is possible. Other methods for parameter adjustment are through frequency–response analysis and Bode diagrams [6]. The Ziegler–Nichols method calculates directly the necessary values for the parameters of PID controllers, while the Bode method evaluates the transfer function of the process. The second method has the advantage that there is no need to shut down ASP for adjustments because the adjusting signal 'from a sinusoidal generator' is applied during the normal operation of the process. However, the sinusoidal signal sometimes is a disturbance that has significant value and

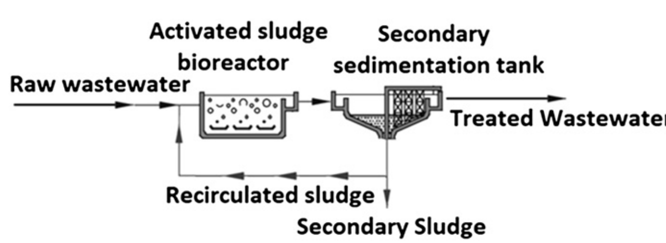

Fig. 1. Conventional activated sludge system.

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causes instability to the operation of ASP. All the aforementioned methods are applied to ASP through a Supervisory Control and Data Acquisition system (SCADA) as shown by reference [7].

Modern automatic control is a system that controls various processes. It uses the feedback of state variables that describe the process to control activated sludge system as shown by [6]. Modern control has the flexibility to place the poles of a system in more desirable locations of root locus *via* the adjustment of its feedback gains (pole placement design) while classical control based on PID controllers cannot always fulfill this task through compensation procedure [7–13].

Regarding the obstacles that modern automatic control has to overcome, it should be mentioned that ASP is a non-linear process and it cannot deviate much from its working point. If there is a large deviation, the process fails as demonstrated in references [5,6]. The inability of state variables' measurement with precision, reliability and in real time is another significant obstacle as demonstrated by literatures [2,7]. The designer of a modern control system, with state variable feedback in complex processes which stem from the combination of simpler sub-processes such as S_O and X_H, has the opportunity to enhance the quality of treated wastewater in a degree that is not possible with the multi-loop classical systems that are commonly used today [14–21]. On the other hand, there is an optimal control such as the optimal regulator which is a complicated system and it is rarely implemented in WWTP.

The main objective of this study was to design a modern automatic control system which uses an I-P modified controller [5] for ASP that will achieve faster system response in reference value changes and smaller fluctuations of the controlled variables to the disturbances of influent flow rate (increased robustness or lower sensitivity) than the same system but with PI controller. Through examination of control variable fluctuation in the transient response region, there is no saturation in its value. As mentioned above a comparison was performed between PI controller and I-P modified controller. That comparison was feasible because the two control systems had the same characteristic equation as it results from Mason gain formula and signal flow graphs (Figs. 2 to 4). ASP was a second order system in this study, combining the oxygen and microorganisms subsystems. The control system was tested with step changes in reference values of S_O and X_H which were symbolized as $S_{O,REF}$ and $X_{H,REF}$ and in step change of the disturbance q_F for both S_O and X_H. A control-canonical form simulation diagram was used for the process and the controller was a modified I-P type with state variable feedback design (or pole placement design). The selected poles were -0.018, $-200.0-200.0\cdot i$ and $-200.0+200.0\cdot i$ for S_O and -8.0, $-7.0+7.0\cdot i$ and $-7.0-7.0\cdot i$ for X_H. Modern control such as this one was not as effective as optimal control but it was simpler and it was not studied extensively for the control of ASP. Additionally oxygen subsystem was combined with microorganism subsystem, a combination which was usually avoided in other studies because of the large difference in the settling times of the two systems (S_O in minutes and X_H in days). This approach has advantages compared to isolated subsystems of S_O and X_H in both settling time and disturbance rejection. I-P controller is different from PI controller in that the proportional part of the controller is fed with the feedback variable and not with the error as it is done with the PI controller. This difference makes the system more robust. When in the reference input there is a step function change then the control signal of the closed loop system will have a step-like shape with overshoot. This is undesirable in many cases where a smoother response is required. By moving the proportional action of the controller in the feedback loop this acts only in the feedback signal and the step like control signal is omitted (Ogata [5]). So the controller I-P is also a PI type as it is shown in Fig. 2 and the difference of I-P with the PI controller is the type of signal the two parts of the controller (proportional and integral) are fed with (error signal or feedback signal). From Fig. 2 it is calculated that if the reference value is zero then for I-P controller: $\frac{M(s)}{Y(s)}=-\left(K_1+\frac{K_3}{s}\right)=-G_c(s)$ which is the transfer function of a PI controller. This calculation shows that if the reference value is zero then the I-P and PI controllers are identical. Changes in the reference values of oxygen and microorganisms (increases by 10%, 20% and 30%) show satisfactory response of the system in all cases. Changes in the value of inlet wastewater flow rate disturbance (increases by 10%, 25%, 50% and 100%) were stabilized by the control system in short time. Maximum percent overshoot is also taken in consideration in all cases and the largest value was 25% which is acceptable.

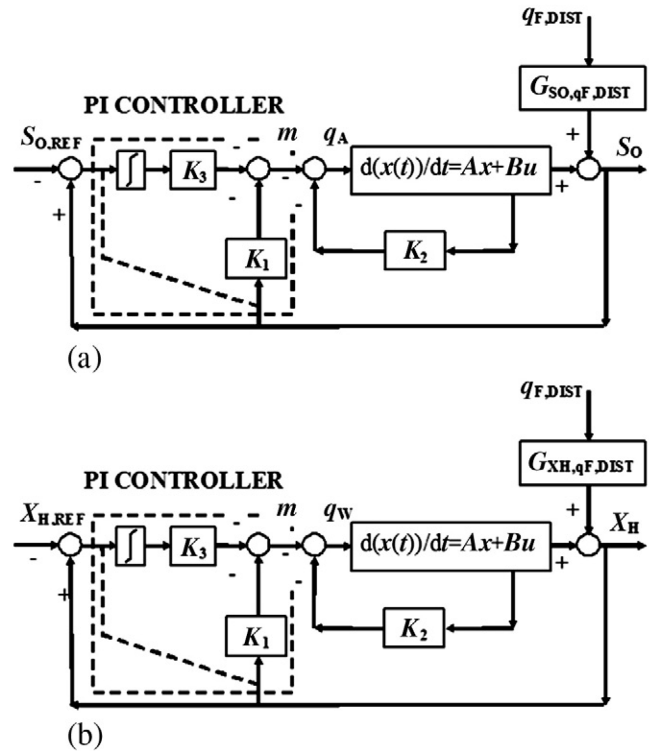

Fig. 2. Modern automatic control system block diagram with disturbance for (a) oxygen and (b) microorganisms [6].

2. Proposed Modified I-P Controller Control System with Pole-Placement Design

An I-P controller control system or modified I-P controller control system with pole-placement design is the modern automatic control system used in this study. A more stable response is achieved with this type of modern control. The modern automatic control system is used as a single input and single output control system but with the feedback of all the state variables of the process which is controlled [6]. The block diagrams of oxygen and microorganisms are presented in Fig. 2. In Fig. 3, it is shown how the process transfer function gives the simulation diagram of control-canonical form. Two control variables (q_W and q_A) are used by the I-P controller control system of this study as input control signals.

Comparisons between the systems presented in Figs. 3(a) and 4(a) are easily done because they have the same characteristic equation according to Mason's gain formula. Also systems in Figs. 3(c) and 4(b) have the same characteristic equation and can be compared. Similarly the signal flow graphs for the q_F disturbance can be drawn. Inlet flow rate (q_F) value change is the external disturbance for the subsystems of S_O as can be seen in Eq. (14) and X_H as can be seen in Eq. (16).