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MODELING OF FUZZY CONTROL SYSTEM OF BIOREACTOR MODULES

Makhmudov Giyosjon Bakoevich
PhD, Associate Professor, Department of General Technical Sciences, Asia International University

Annotation: In this paper, a new modeling methodology is developed to develop a mathematical model of a bioreactor used in the bacterial oxidation process. Based on the results of the literature analysis, a comparative analysis was carried out with the existing model. To adjust the parameters in the bioreactor, the coefficients of the fuzzy PID controller were adjusted based on the specified settings. The effectiveness of the proposed method is proven by comparing the methods for tuning controllers presented in the literature. The results of the study show that the proposed method is highly effective with rational regulation of bioreactor parameters. In addition, the proposed method was tested in the nonlinear state of a bioreactor model for the presence of noise during the measurement process.
Key words: fuzzy controller, genetic algorithm, neural network, control system, programmable logic controller, bioreactor.

Introduction. Today, as the main production sector of the economy of our republic, great attention is paid to the creation of modern energy and resource-saving management systems for bacterial oxidation processes in the mining industry. The new Strategy for the Development of Uzbekistan for 2022-2026 sets out the following tasks: “To reduce losses in industrial sectors and increase the efficiency of resource use ..., to introduce modern energy-saving technologies, equipment and renewable energy sources, to manufacture renewable energy devices and to finance projects to increase energy efficiency” [1]. In fulfilling these tasks, one of the priority tasks is to create an intelligent management system for the bacterial oxidation process of complex gold-containing sulfide ores, using modern technological means.
The processing of sulfide ores in the bacterial oxidation process is carried out after the flotation process. In these processes, bioreactors play a key role for the development of bacteria. Since bacteria are living organisms in the bioreactor system, in order to provide the necessary conditions for them, 48 bioreactor modules in the biooxidation shop at the 3rd GMZ (Hydrometallurgical Plant) of the Navoi Mining and Metallurgical Combine JSC are currently fully automated. The biocake produced from the bacterial oxidation process depends on the quality indicators of the control system. In this case, the control system must monitor and control the state of the bacteria and their growth. In addition, the bioreactor may stop working as a result of internal and external disturbances. In this case, if accidents occur in the control of the bacterial oxidation process, it is clear that a huge amount of economic damage will be caused. Therefore, there is a need for new control methods to ensure the continuous operation of bioreactor modules that are resistant to disturbances, to quickly start up, and to automatically adjust bioreactor parameters [2].
Methodology. The problem to be solved and the research method/methodology of the problem. Various literatures were studied on the development of reliable controllers operating in one or more steady states to adjust the parameters of the bioreactor system.

In the article [3], the authors studied intelligent control systems on the example of multi-input bacterial oxidation processes. A mathematical model and structural scheme of the technological process were developed through experimental research in various operating environments in the established mode.
In the work [4], a modeling method based on recurrent neural networks for a nonlinear bioreactor operating in a steady state and a predictive nonlinear model controller were proposed to obtain the desired result.
Professor Zoltan K Nagy of Loughborough University, UK, proposed a predictive control method based on neural networks for a bioreactor model. According to him, based on the modeling results, it was concluded that the proposed predictive control method based on neural networks can increase the efficiency compared to the linear MPC PID controller [5].
In [6], Indian scientists discussed a method for tuning a PI controller based on a genetic algorithm (GA) for controlling a bioreactor system operating in a stable fixed mode.
In [7-9], many leading foreign scientists emphasized the instability and complexity of a bioreactor system operating in an unstable stationary mode.
In the study of the literature on the control of bacterial oxidation technological processes, methods based on predictive models, neural networks, genetic algorithms and PID controllers were proposed for controlling this process. Many methods have been studied for tuning a PID controller, which require numerical calculations to determine the optimal parameters of the controller in stable and unstable systems [10-11].
To date, special attention is paid to the development of software calculation methods in order to reduce the calculation time for finding the values of the parameters in tuning a PID controller.
The method of using a fuzzy method for tuning the parameters of the PID controller is one of the most effective methods. Recently, much work has been done in engineering to analyze optimal methods for tuning the parameters of the controller in programmable logic controllers. This article is devoted to the use of a fuzzy tuning algorithm for optimizing the parameters of the PID controller. This method does not require the creation of a complete mathematical model of the controlled process [12-13].
In the article [14], Chinese scientists proposed a generalized optimization algorithm for tuning the PID controller for a nonlinear system with a swinging pendulum.
Literature analysis shows that for nonlinear systems in various steady states, effective control can be achieved using planned amplifier control systems [15]. Such a control system includes a control unit and a switching (main) control unit. The main control unit transmits the control effect to the control unit based on the given technological regulations in order to ensure effective control of the entire bioreactor system.
A fuzzy tuning algorithm based on the objective function is proposed to adjust the parameters of the PID controller. The tuning of the controller is carried out separately for stable and unstable states of the bioreactor system. The PID controller adjusted based on the fuzzy algorithm is used to control the bioreactor system in full-state. The effectiveness of the proposed control system can be justified by using a nonlinear bioreactor model [16].
The main reaction of the bacterial oxidation process inside the bioreactor is expressed as follows:

$$R \xrightarrow{v_d} M \tag{1}$$

where, "R" is the reagent, "vd" is the reaction rate constant, and "M" is the product.

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Equation (1) describes the biooxidation process. In the bacterial oxidation process, the main factors are ensuring that the main parameters are in accordance with the technological regulations and that the bacteria are supplied with food in a timely manner.

For the stable operation of this process, it is advisable to adjust the pH, pulp temperature, mixer rotation speed, and compressed air pressure in the bioreactor to provide oxygen. If the above parameters are adjusted according to the regulations, the bacteria will actively develop in the process. During the bacterial oxidation process, a living organism develops inside the bioreactors and is directly fed with a substrate. In the initial period of the bacteria, technological parameters must be adjusted so that they can develop in a new environment. To increase the productivity of the technological process, it is necessary to install a programmable logic controller. Here, the controller is used to control the concentration of the bacterial mass and the concentration of the substrate. By optimizing the parameters of the fuzzy controller, the concentration of bacteria and the substrate in the bioreactor are stably adjusted based on the proposed model. The main goals of introducing a fuzzy controller for the bioreactor system are to maximize production efficiency and reduce the content of rare metals in the waste [17].

The stoichiometric activity of bacteria is very complex and depends on environmental conditions, nutrient consumption, and parameters in the bioreactor. For these reasons, bioreactor models were considered for analysis.

Mathematical models of various industrial bioreactors are represented as follows:

$$\frac{dX}{dt} = (\mu - D)X, \qquad \frac{dS}{dt} = D(S_f - S) - \frac{\mu X}{Y}, \tag{2}$$

$$\frac{dP}{dt} = -DP + (\alpha\mu + \beta)X, \qquad \mu = \frac{\mu_{\max} S}{K_m + S}, \tag{3}$$

where "μ" is the specific growth rate of bacteria, "X" is the biomass concentration, "S" is the substrate concentration, "α" and "β" are the parameters of the outgoing biocake. In the steady state, the variables are equal to $X = X_s$, $S = S_s$ and $P = P_s$. According to equation (2), in the fixed mode, it is expressed as follows:

$$\frac{dX_s}{dt} = 0, \qquad \frac{dS_s}{dt} = 0. \tag{4}$$

Developing a real-time bioreactor model is a complex task and sometimes it is not considered a satisfactory model due to its nonlinear nature. The duration of the bioreactor operation is much longer than that of other types of chemical processes. Typically, industrial bioreactors can operate for several days for the process to fully proceed. Developing a real-time bioreactor model requires a lot of time to collect data. Therefore, in this article, it is proposed to develop a mathematical model of the bioreactor based on a literature review. In this work, the mathematical model of the bioreactor in the form of an equation of state is developed based on equations (2) and (3). According to the mathematical descriptions given above, it is proposed to give the spatial equation of state of the system as follows. Based on the formalization performed,

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we write the dynamics and state equations of large-scale systems consisting of four interconnected subsystems, each of which is usually described by the following equation [18]:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + f(t), \\ y(t) &= Cx(t). \end{aligned} \tag{6}$$

where,

$$\begin{aligned} A &= \begin{bmatrix} \mu_s - D_s & X_s \mu_s' \\ \dfrac{-\mu_s}{Y} & -D_s - \dfrac{-\mu_s' X_s}{Y} \end{bmatrix}, \\ B &= \begin{bmatrix} -X_s \\ S_f - S \end{bmatrix}, \\ C &= [1 \quad 0]; \qquad D = [0], \end{aligned} \tag{7}$$

where, μ_s, D_s, Y, S, S_f, and X_s are the final values of the bioreactor at steady state during model development.

These values were implemented in equation (7) to develop a model of the bacterial growth and steady-state bioreactor. The mathematical model of the bioreactor in the form of an equation of state was developed as follows:

$$\begin{aligned} A &= \begin{bmatrix} 0 & -0{,}064 \\ -0{,}77 & -0{,}1298 \end{bmatrix}, \\ B &= \begin{bmatrix} -0{,}9883 \\ 2{,}5104 \end{bmatrix}, \\ C &= [1 \quad 0]; \quad D = [0] \end{aligned} \tag{8}$$

Figure 1 shows the relationship between biomass concentration and substrate concentration in the bioreactor.

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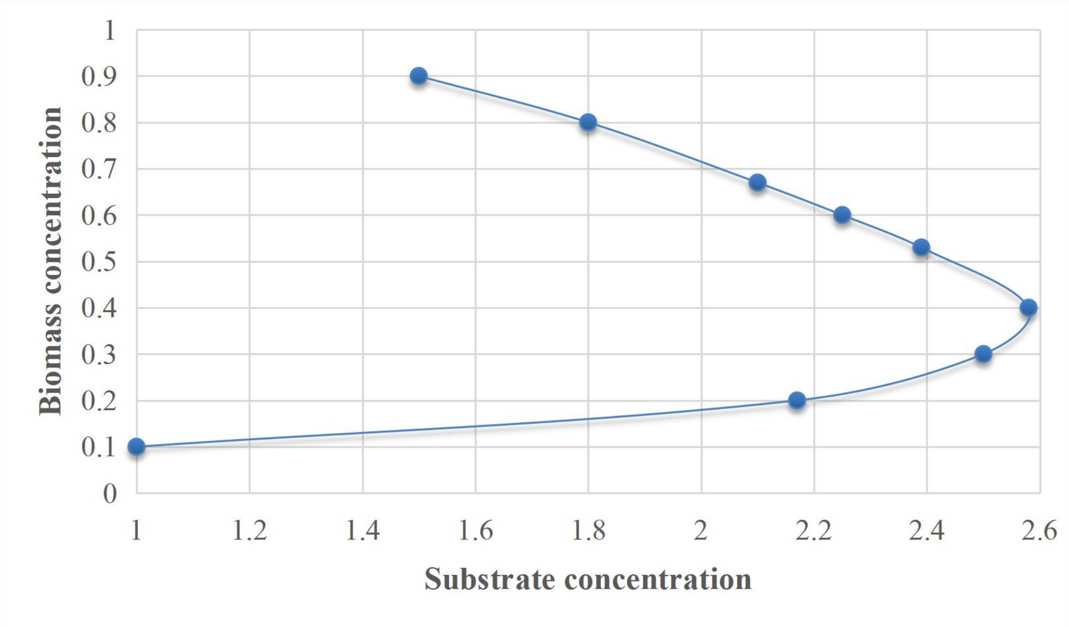

Figure 1. Graph of the relationship between biomass and substrate concentration in the bioreactor

Initially, the biomass concentration increases linearly with the substrate concentration. Then, when the maximum growth rate of bacteria is reached, the biomass concentration continues to increase, even if the conditions in the bioreactor are maintained with a small amount of feed.
The lowest cost of control and actuators was taken as the main criterion in the formation of the knowledge base. In addition, the main reason for using fuzzy controllers for the control system of the bacterial oxidation process is that when analyzing the performance of two controllers, namely the traditional PID and the fuzzy controller, the performance of the fuzzy controller is better, as can be seen from the comparison table below [19].
1-table

Types of regulators	**Quality indicators**			
	Time to reach setpoint (s)	Extreme regular (^{0}C)	Regular time (s)	Error (%)
PID	48,3	21,7	72	0,78
Fuzzy regulator	19,6	4,8	52	0,23

Analyzing the literature presented in the framework of the scientific research work, it can be noted that the use of fuzzy logic controllers in solving the problems of creating intelligent control systems for the bacterial oxidation process has a number of advantages. In this regard, the research work is based on the use of fuzzy set models and fuzzy logic methods to create an intelligent control system for the bacterial oxidation process of complex gold-containing sulfide ores based on a fuzzy controller. Since these methods allow for the implementation of a highly efficient control process, taking into account various parametric uncertainties occurring in the object, the variability of the object properties over time, and the interdependence of various factors affecting the process [20].

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The expression of a PID controller with a parallel structure for controlling nonlinear systems is considered.

$$K_P\left(1+\frac{1}{\tau_I s}+\tau_D s\right) = K_P+\frac{K_I}{s}+K_D s \tag{9}$$

where, $\tau_I = K_P/K_I$, $\tau_D = K_D/K_P$. - integration and differentiation time. The fuzzy PID controller tuning process is used to find the best possible values of K_P, K_I and K_D. To achieve maximum accuracy in finding the optimal value of the coefficients, it is necessary to implement a fuzzy algorithm.

When tuning the PID controller, the optimal values of its parameters (K_P, K_I, K_D) are found by minimizing the objective function. It is advisable to use optimization algorithms to determine the appropriate values of the controller parameters.

A comparative graphical analysis of the tuning graphs of the controllers (PI, PD, PID) published in the studied literature was carried out with a fuzzy PID controller. It can be clearly seen in Figure 6 that the proposed fuzzy PID controller increases the efficiency of the bacterial oxidation process, the tuning time is fast, the tuning and oscillation indicators are much better than the others. The resulting graphical representations characterize the dependence of the input variable of the fuzzy controller on the output variable. When using a fuzzy controller for the automatic tuning system of the bacterial oxidation process, creating a program for programmable logic controllers effectively increases the quality indicators of tuning. A comparative graph of the transient characteristics of a fuzzy controller and a traditional PID controller was obtained in the Matlab application environment as follows.

Based on the results of the simulation modeling, theoretical conclusions can be drawn, namely, the synthesized automatic control system with a fuzzy controller, under conditions of uncertainty in the external environment affecting the bacterial oxidation process, ensures stable maintenance of the bioreactor temperature at the required value and allows for high-quality control of the technological process even when the parameters of the facility change over a wide range.

Conclusion. Building a fuzzy control system based on a model of a bioreactor in a bacterial oxidation process is a complex task. This article presents the modeling and development of a fuzzy PID controller based on a nonlinear bioreactor model. The bioreactor model is expressed in the form of a state equation based on the results of experimental measurements. The article presents the algorithm created for developing a mathematical model of a nonlinear bioreactor and its description. In addition, the structural scheme of the fuzzy control and the obtained comparative graph and its analysis, as well as methods for adjusting the coefficients of the fuzzy PID controller are presented. According to the presented research work, it can be concluded that the proposed controller is resistant to external disturbances and provides stable adjustment of the process. It can be seen that the fuzzy PID controllers are effective in terms of fast adjustment time in stabilization compared to the controllers presented in other literature in controlling nonlinear systems.

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