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Design of Fuzzy Control System for Dissolved Oxygen Concentration in Aeration Tank

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Authors' contributions

This work was carried out in collaboration between both authors. Author YL designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author LL managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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Short Research Article

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ABSTRACT

The effluent quality of the wastewater treatment is significantly influenced by the amount of dissolved oxygen in the wastewater aeration tank. In this paper, we design a fuzzy control system to regulate the concentration of dissolved oxygen in the aeration tank based on the fact that the control process of dissolved oxygen concentration in actual engineering is characterized by nonlinearity, large fluctuation, and severe hysteresis. The dissolved oxygen concentration is real-time controlled by the control system using the dissolved oxygen concentration as the controlled variable and the aeration of the blower as the manipulated variable. The simulation of the fuzzy control system using MATLAB software demonstrates that the response of the control system to the level of dissolved oxygen in the aeration tank is accelerated, and the outcome has strong robustness and good stability. With this design, the aeration tank's energy loss is decreased while the efficacy of the wastewater treatment is maintained.

Keywords: Dissolved oxygen; aeration tank; fuzzy control; blower; MATLAB.

1. INTRODUCTION

Aeration tanks are essential in the biochemical treatment of wastewater [1]. About 60% of the energy consumption of wastewater treatment comes from the aeration basin, it is critical to investigate the energy consumption of the degradation aeration basin to ensure effluent

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quality [2]. Systems for treating wastewater typically have multiple modes, time-varying parameters, and significant disturbances. Changes in influent flow and sludge load disturbances can cause dissolved oxygen concentrations to fluctuate. Low dissolved oxygen concentration can cause aerobic bacteria in the aeration basin to react insufficiently, which in turn reduces their activity when microorganisms in the aeration basin are performing biochemical reactions [3–5]. The slower rate of aerobic bacteria growth results in longer wastewater treatment times and poorer effluent quality. When the dissolved oxygen concentration is high, the continuous aeration process consumes a lot of energy, and the increased biofilm scouring causes microorganisms to die [6,7]. Therefore, the effluent quality of the wastewater treatment system is significantly impacted by the judicious control of the dissolved oxygen concentration in the aeration tank. The effectiveness of wastewater treatment is significantly impacted by the traditional dissolved oxygen concentration control system's slow response time, complex process, high energy consumption, and poor economy. The stability of dissolved oxygen concentration management has been enhanced by studies in the literature [8,9], however, there are still issues with energy consumption and efficiency.

To address the aforementioned issues, this paper proposes a fuzzy control system for regulating the concentration of dissolved oxygen in the aeration tank.

Fuzzy control is an intelligent control method based on fuzzy set theory, which uses multi-valued fuzzy logic and artificial intelligence elements to imitate human thinking and reactions [10]. The fuzzy control, unlike the traditional control, does not need to establish an accurate mathematical model like the traditional control, but it needs to have long-term summarized data or relevant equipment use experience, which is effective for the non-linear and large inertia system.

The core of fuzzy control is the fuzzy controller. The basic principle of a fuzzy controller is to fuzzify the input digital signal into a fuzzy quantity and send it to a fuzzy inference module that contains fuzzy control rules, in which the fuzzy set is obtained by approximate inference [11]. The fuzzy set is transformed into the clear quantity by the clarification module and then exported to the next level for adjusting the controlled object to make it output a satisfactory result. There are two commonly used fuzzy controllers, the Mamdani and the Sugeno [12]. The system design in this paper is based on the fuzzy controller of Mamdani. The basic components of the Mamdani fuzzy controller are shown in Fig. 1.

In Fig. 1, the digital variable and its rate of change are input on the left and the exact variable is output on the right, which is a very typical two-dimensional controller. In the orange part, 'μ' represents the library of affiliation functions, which stores the affiliation functions for converting digital quantities to fuzzy quantities; 'R' represents the control rule bank, which stores the F-conditional statements for performing approximate inference and the algorithms for approximate inference; 'fd' represents the library of clarification methods, which stores the algorithms used to perform clarification on fuzzy quantities. In the purple part, 'D/F' represents the fuzzification module, which operates by converting clear quantities into fuzzy quantities; 'A*∘R' represents the approximate inference module, which completes the approximate inference operation based on the input

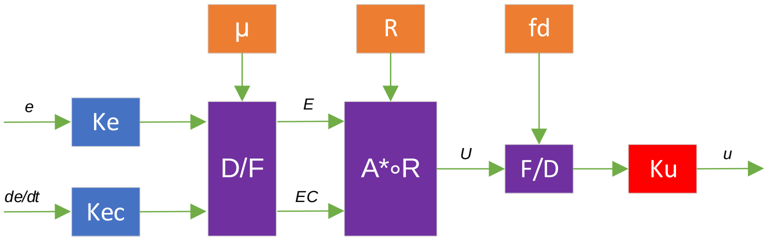


Fig. 1. Block diagram of the fuzzy controller with Mamdani
e: Digital variable; de/dt: rate of change; E: Fuzzy variables; EC: Rate of change of fuzzy variables; U: Inferred fuzzy variable; u: Inferred clear variable; Blue part: Quantitative factor; Orange part: Knowledge Bank; Purple part: Core of fuzzy controller; Red part: Scale factor;

fuzzy quantity; ‘F/D’ represents the clarification module or the anti-fuzzification module, which completes the operation of converting fuzzy quantities into clear quantities. The blue part and the red part have proportional scaling for the clear signal of the input and output of the fuzzy controller, which is the input and output interface of the fuzzy controller [13–15].

2. MODELING AND DESIGN OF FUZZY CONTROL OF DISSOLVED OXYGEN CONCENTRATION IN THE AERATION

The widely used methods for biochemical process control in wastewater treatment systems are manual control and conventional PID control. In the absence of an accurate biochemical process control model, conventional PID control is not very effective [16,17]. In addition, it is assumed that just to increase the complexity of the control system, there will be not only the unstable operation of the controller but also difficult to manipulate by the staff and other conditions.

Under the premise of ensuring the efficacy of wastewater treatment and reducing the energy consumption of the aeration system, the controlled variables usually cannot be selected in a segment where the influent flow or water quality fluctuates significantly [18]. The dissolved oxygen concentration in the aeration tank effluent was studied to be 2.0 mg/L to 2.5 mg/L, a range suitable for the growth of aerobic microorganisms. The amount of oxygen required by the wastewater during the aeration time is related to the biological oxygen demand, chemical oxygen demand, and suspended solids, and the blast volume can be adjusted according to the water quality and quantity. We choose dissolved oxygen concentration as the controlled variable. Dissolved oxygen online detection is simple and highly reliable so that the dissolved oxygen concentration can be maintained within 2.0mg/L to 2.5mg/L by simply detecting the dissolved oxygen concentration and adjusting the blower blast volume in real-time. This method allows the microorganisms in the biochemical tank of the wastewater treatment system to carry out normal biological activities, facilitating the decomposition of organic matter and maintaining sludge activity.

2.1 Fuzzy Control Scheme

The control system model established in this paper uses the concentration of dissolved oxygen in the sludge mixture in the aeration tank as the controlled variable and the aeration volume of the blower as the manipulated variable. According to the characteristics of the system, a simple and easy-to-analyze two-dimensional fuzzy control system is selected, and the control process block diagram is shown in Fig. 2.

In this study, a frequency converter is used to control the blower frequency. The deviation and rate of change in the deviation between the dissolved oxygen value detected in real-time by the determinator for dissolved oxygen are selected as the two-dimensional input variable of this fuzzy controller. In actual operation, the dissolved oxygen value is set by the upper computer or touch screen, and then the dissolved oxygen concentration in the aeration tank is detected by the dissolved oxygen online tester in real-time. The dissolved oxygen concentration control inverter sets the frequency to adjust the blower's blowing volume in real-time so that the dissolved oxygen concentration of the aeration tank can be controlled in the appropriate range. This ensures the effectiveness of the wastewater treatment and thus achieves the purpose of improving the efficiency of the wastewater treatment.

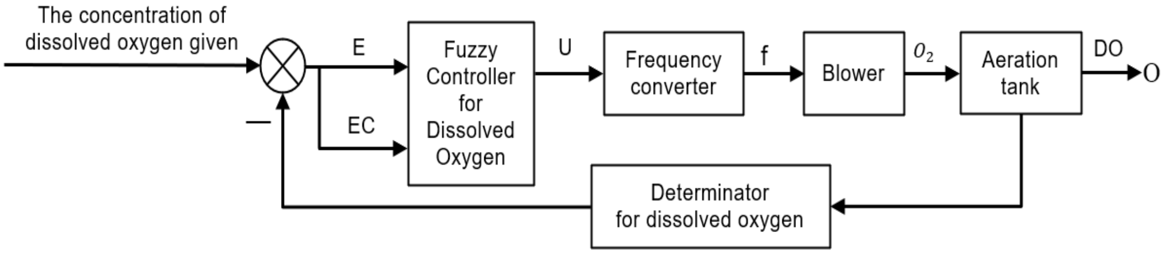


Fig. 2. Block diagram of dissolved oxygen concentration control system

2.2 Equivalent Mathematical Model

The equivalent mathematical model of dissolved oxygen concentration in the aeration process can be established after determining the fuzzy control scheme for the aeration of the aeration tank. Since the aeration link in wastewater treatment is a complex dynamic process that is difficult to define with an accurate mathematical model, certain assumptions need to be made when building an approximate simulation model.

Assumption 1: the aeration process is spatially perfectly mixed and temporally ideal for push-flow variation.

Assumption 2: In one cycle, the total biomass in the aeration tank is approximately constant compared to the total biomass, which can be neglected for the number of synthesized microorganisms.

Assumption 3: The dissolved oxygen concentration of the effluent from the previous cycle in the aeration tank is negligible compared to the raw water concentration until the start of a new cycle.

Assumption 4: The reaction rate of the established wastewater is set as a constant.

According to the equilibrium relationship of dissolved oxygen concentration in the aeration tank, the following dynamic control equation 1 is established.

$$\boldsymbol{V\frac{dC}{dt} = QC_0 - QC_1 - KVC} \qquad (\mathbf{1})$$

In Equation 1, 'V' represents the volume of the aeration tank; 'Q' represents the airflow into the aeration tank; 'C' represents the dissolved oxygen concentration in the aeration tank; 'C_0' represents the dissolved oxygen concentration in the drummed air; 'C_1' represents the dissolved oxygen concentration in the tailwater; 'K' represents the reaction rate constant.

Performing Laplace transform on equation 1, we can obtain equation 2.

$$G(S) = \frac{C_0 - C_1}{Vs + VK} = \frac{(C_0 - C_1)/V}{s + K} \qquad (2)$$

Equation 2 represents an inertial link when the upper part of Equation 2 is considered as a whole. Since the detection of dissolved oxygen concentration usually lags, the model of Equation 2 should be modified. Introducing a lag time to represent the dissolved oxygen concentration detection lag, Equation 2 can be corrected to Equation 3.

$$G(S) = \frac{(C_0 - C_1)/V}{s + K} e^{-\tau s} \qquad (3)$$

Equation 3 can be considered as an approximate simulation model of aeration in an aeration tank and can be simplified to a first-order inertial link in series with a first-order lag link. Equation 4 is used to represent its transfer function. The parameters 'K', 'T', and 'τ' directly reflect the characteristics of the aeration process.

$$G(S) = \frac{K}{Ts + 1} \qquad (4)$$

2.3 Design of Fuzzy Control for Dissolved Oxygen in the Aeration Tank

We defined the theoretical domain of the dissolved oxygen concentration input deviation from minus two to plus two and the deviation rate of change in the range of minus 0.05 to plus 0.05. based on the analysis of the dissolved oxygen concentration in the aeration tank aeration process. The number of discrete elements is usually taken from 5 to 15 because it is important to consider that the fuzzy set can cover the theoretical domain well and avoid excessive computation. The system described in this paper has a quantization level of thirteen for both input deviation and output control quantity, and a quantization level of nine for the rate of change of deviation. The fuzzy division is related to the number of elements in the discrete domain. According to the relationship between fuzzy division and quantization level, the total number of fuzzy division terms is about one-half in the discrete domain. Therefore, it can be concluded that there is a fuzzy subset of input deviation and output control quantity of dissolved oxygen concentration, and there are five fuzzy subsets of deviation change rate.

The system designed in this paper uses trapezoidal and triangular current membership functions to describe each fuzzy variable, and the ascending semi-trapezoidal function determined by the parameters 'a', and 'b' is expressed in the form of Equation 5. The descending semi-trapezoidal function part is represented by Equation 6, and the triangle current membership function part is represented by Equation 7.

$$f(x,a,b)=\begin{cases}0 & x\le a\\ \dfrac{x-a}{b-a} & a\le x\le b\\ 1 & x\ge b\end{cases}\tag{5}$$

$$f(x,a,b)=\begin{cases}1 & x\le a\\ \dfrac{b-x}{b-a} & a\le x\le b\\ 0 & x\ge b\end{cases}\tag{6}$$

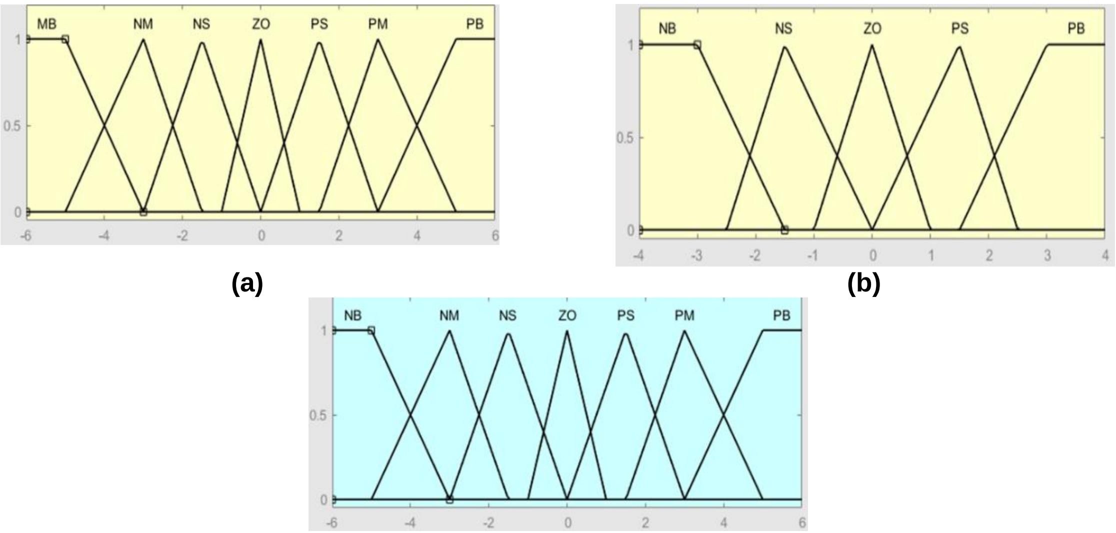
$$f(x,a,b)=\begin{cases}1 & x\le a\\ \dfrac{c-x}{c-b} & a\le x\le b\\ \dfrac{c-x}{c-b} & b\le x\le c\\ 0 & x\ge c\end{cases}\tag{7}$$

We can get the current membership functions of input deviation, input deviation change rate, and output control quantity by applying Equation 5, Equation 6, and Equation 7 to get the values of ‘a, ’b’, and ‘c’, as shown in Fig. 3.

According to the changing relationship between dissolved oxygen concentration, blower blast volume, and the practical experience of operators, we summarized 35 fuzzy control rules and show them in Fig. 4. The red block in Fig. 4 stands for E, the purple block for EC, and the blue block for U. The various colored lines depict various fuzzy control principles. As an illustration, if (E is NB) and (EC is NB) then (U is PB). Fig. 4 shows the fuzzy control rules in the case as blue lines connected to various colored blocks. We use the weighted average method, a fuzzy judgment method, to calculate the actual output in this system. The set value of dissolved oxygen concentration is compared with the detected value of the detector to obtain the input deviation and the input deviation change rate. Then after fuzzifying the input deviation and input deviation change rate, the output control quantity is obtained by querying the fuzzy control table, and then the output control quantity is anti-fuzzified to obtain an accurate single value. Finally, this accurate value was used to control the blower's blast volume.

3. FUZZY CONTROL SYSTEM SIMULATION IN MATLAB

MATLAB is a kind of visual computing software that is widely used nowadays and can perform high-performance calculations. It integrates numerical analysis, matrix operations, signal processing, and graphical display, constituting a convenient and friendly user environment. In this paper, the MATLAB R2020 version is used, and the basic tool for fuzzy system simulation is the graphical user interface.



(a)

(b)

(c)

Fig. 3. Current membership function image

(a): Current membership function image of input deviation; (b): Current membership function image of input deviation change rate; (c): Current membership function image of output control quantity

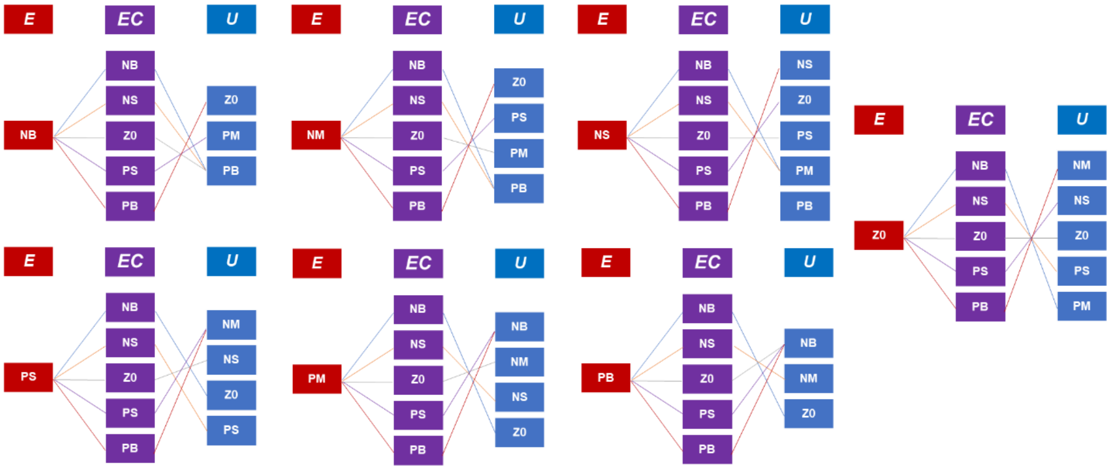
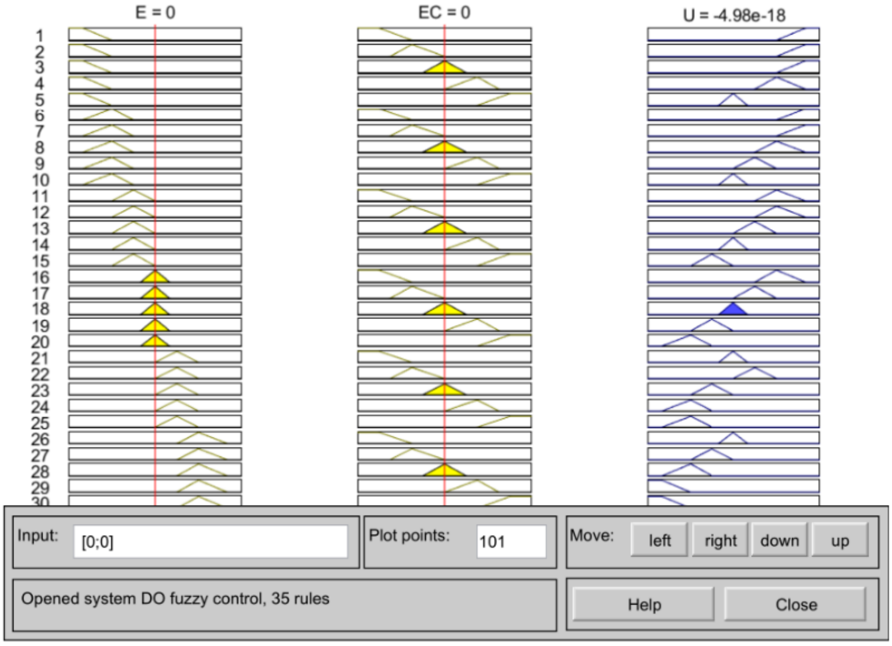


Fig. 4. Fuzzy control rules

3.1 Fuzzy Control System Settings

Based on the method described in Section 2, we set up the corresponding input and output variables in the FIS editor interface of MATLAB and select the Mamdani-type fuzzy control rules. Then we set the name, type, display range, and corresponding parameters of the corresponding current membership function in the current membership function editor. The image of the corresponding current membership functions has been shown in Fig. 3.

We entered the fuzzy control relationship shown in Fig. 4 at ruler editor. We then used the RULE VIEWER to observe the complete process of fuzzy inference and determined whether the fuzzy inference system was operating as intended by the design. The interface of the fuzzy RULE VIEWER is shown in Fig. 5. The three sets of rectangles in the viewer correspond to three variables, and the triangles within each rectangle correspond to its current membership function. The triangles of the input variables are yellow and the triangles of the output variables are blue, and each row corresponds to a fuzzy control rule.



Input: [0;0]

Plot points: 101

Opened system DO fuzzy control, 35 rules

Fig. 5. Fuzzy rule viewer window

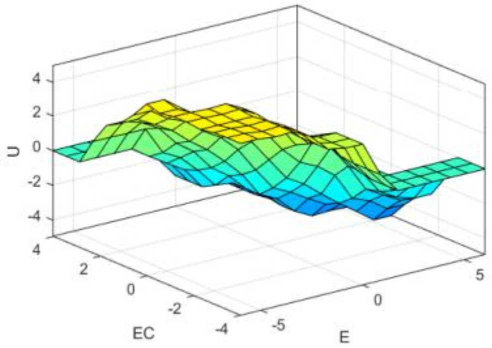


Fig. 6. Fuzzy rule surface graph

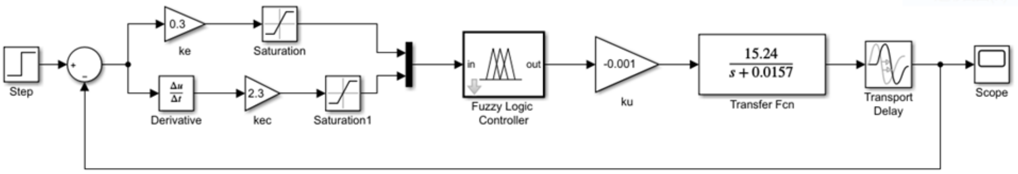


Fig. 7. Simulation model of fuzzy control

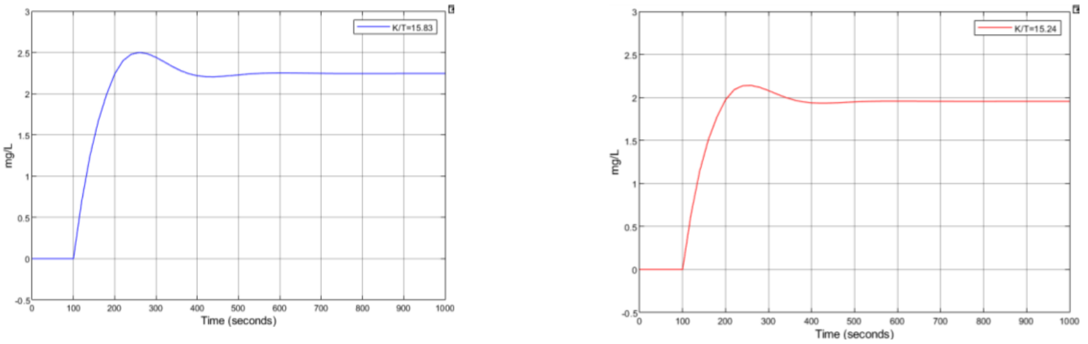
A fuzzy inference system maps given inputs to outputs using fuzzy logic. The mapping of a two-input, one-output fuzzy controller designed in this paper can be depicted in a 3-D plot which is shown in Fig. 6. We obtained the output surface of fuzzy inference using the observer, as shown in Fig. 6. This surface graph can reflect the input-output relationship of this fuzzy control system.

For control applications, the FIS inputs are the error and change of error, E and EC respectively in the control surface plot. The FIS output is the control action inferred from the fuzzy rules, u in the surface plot.

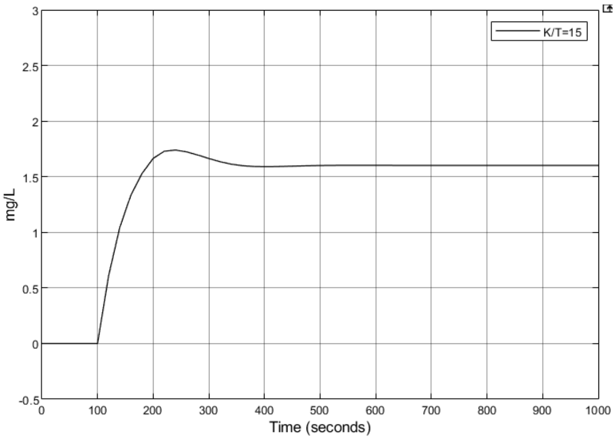
3.2 Building a Simulation Model of Fuzzy Control System

The simulation model shown in Fig. 7 was built using the Simulink module in MATLAB. We enter the fuzzy system saved in MATLAB into the " Fuzzy Logic Controller" in Fig. 7, connect the fuzzy inference system and the fuzzy controller module, then connect the rest of the modules and set the parameters.

Based on the simulation results in Fig. 8, negative feedback in the simulation model continuously modifies the input signal until the output signal reaches a steady state. It can be obtained that when the input is a step signal and the parameter is set to ‘K/T=15’, the curve can reach the set value relatively quickly, i.e., the response speed is fast and the steady-state error is close to ‘1.5 mg/L’ at the minimum, which meets the expected requirements of this fuzzy control system, thus verifying that the fuzzy control method applies to the dissolved oxygen concentration control in the actual aeration tank.



(a) **(b)**



(c)

Fig. 8. Simulation results

In a traditional control, the steady-state inaccuracy of the dissolved oxygen concentration ranges from ‘2 mg/l’ to ‘3 mg/l’. The steady-state inaccuracy of the dissolved oxygen content with fuzzy control is ‘1.5 mg/l’, which is better than the traditional control in terms of energy savings.

4. CONCLUSION

Targeting the problem that the dissolved oxygen concentration in the aeration tank is difficult to be adjusted quickly in the wastewater treatment process, this paper designs a fuzzy control system to regulate the concentration of dissolved oxygen in the aeration tank. The feasibility of the design solution was demonstrated by simulation experiments conducted by MATLAB. The experimental results demonstrate that the fuzzy control system proposed in this study may significantly increase the dissolved oxygen concentration regulation speed, which in turn accelerates wastewater treatment efficiency. The increase in wastewater treatment efficiency has resulted in a reduction in the aeration tank's working time for treating the same volume of wastewater, resulting in a reduction in the aeration tank's energy loss. The design made the dissolved oxygen in the aeration tank stabilized, which effectively reduced the possibility of blower breakdown and brought a good energy-saving effect.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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