Study on Application of Fuzzy Control Model in Phosphate Removal Control System of Sewage Water

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Abstract: The precise input of flocculant (PAC) and coagulant aid (PAM) into phosphate wastewater is a key problem to degrade the phosphate content in sewage water and make the total phosphate (TP) and suspended pollutants (SS) in sewage water reach the discharged standard. In this paper, a new method combining fuzzy control technology with wastewater treatment control system is proposed to establish an automatic control system suitable for phosphates removal treatment. Based on experiment data and current experience, the membership function and fuzzy rules are set, and the fuzzy control technology is obtained with simulation analysis, and the efficient treatment of sewage water was realized. It can be seen from the results that the fuzzy control technology could be applied to the phosphate removal control system for treating sewage water, and the standard of stable, accurate and efficient sewage treatment has been realized.
Keywords: Sewage Water Treatment; Automatic Control System; Fuzzy Control Technology; Simulation Analysis.

Highlights:

- Precise input **of** flocculant (PAC) and coagulant aid (PAM).
- The output of total phosphates (TP) and suspended pollutants (SS) reach pollutant water discharged standard.
- A new method combining fuzzy control technology with wastewater treatment control system was proposed.
- The fuzzy control technology is obtained through simulation analysis.
- The high efficient treatment of phosphate mine sewage has been realized.

0 Introduction

Fuzzy control refers to a system that simulate the uncertainty concept of human brain judgment and thinking mode to solve the unknown or uncertainty problems. The fuzzy control system uses fuzzy sets and fuzzy rules to infer the controlled objects with strong nonlinearity and time lag, to express the transitional boundary or qualitative knowledge, to carry out fuzzy comprehensive judgment, and deduce the fuzzy information problems, which is difficult to solve by conventional methods[Shi Xinmin, Hao Zhengqing. 2015]. Compared with the traditional controller, fuzzy control system does not need to establish an accurate mathematical model for the controlled object, but only needs to accumulate the operation experience of the controlled system or the relevant data which can be solved by establishing the fuzzy model[Verbist, K, Brunetti, G, Simunek, J., Bautista, E., 2018.]. Fuzzy control method is an important part of smart control system[LEE H W，et. al. 2010, RAZMKHAH H，

et al. 2010.].

A PLC controller has the advantages of high reliability, flexible programming and low failure rate, and is widely used in the current control industry[NIKOO, et al. 2014, OMID. et al. 2014]. With the increasing complexity of controlled system, the traditional PLC control system can not meet the complex control requirements[Rao R. 2016, APHA American Public Health Association .2005], so it is a very important research topic to introduce fuzzy control technology into the PLC control system. This paper firstly uses Matlab[Mukate S, et al. 2019] to make fuzzy control rules, and then transfer the data to PLC controller. With the advantage of Matlab simulation system in solving complex operation and the characteristics of PLC control system, a fuzzy control system using fuzzy control algorithm is designed for phosphate sewage water treatment[Simeonov V, et al. 2003, Tyagi S, et al. 2013]. Because the method of PLC is impossible to establish an accurate mathematical model for the sewage water treatment system[Molden, et al. 2020, Gen, M., and R. W., Cheng. 1997], therefore, it is an innovation to use fuzzy control model which does not need precise mathematical model to realize the automatic control for sewage water treatment systems.

1 Composition and function of the system

The purpose of phosphate sewage water treatment control system is to realize automatic treatment of phosphate wastewater and domestic wastewater[Choi H. & Lee SM. 2013, Eze VC, et al.V 2018], including intelligent control system and different treatment units, with such treatment system, the phosphate in wastewater can be degraded by inputting flocculant (PAC) and coagulant aid (PAM) into the wastewater to meet the discharged standard. The composition of phosphate wastewater treatment control system is shown in Fig.1.

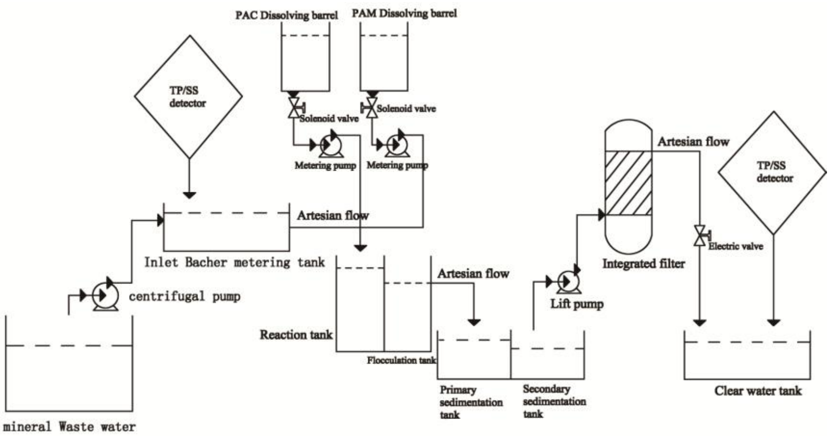

Fig.1 Composition of phosphate rock sewage treatment control system

The treatment system consists of control cabinet, different kinds of pipes, solenoid valve, electric valve, total phosphates (TP / SS)(suspended pollutants) monitor, integrated filter, various pumps, etc. In the system, a centrifugal pump extracts wastewater into the treatment system with unchanged volume. Since the sewage water flow is constant, the dosage of flocculant (PAC) and coagulant aid (PAM) are mainly determined according to the total phosphates (TP) and SS(suspended matter) in sewage water. The sewage treatment process is as follows;

There is a Barschel metering canal to monitor total phosphates TP and SS value. Sewage water flows into the reactor pond, configure the solution according to a certain proportion in

the PAC/PAM solution barrel, The solenoid valve is opened and the frequency converter is controlled by the PLC according to the total phosphates and SS value in the sewage water, and the PAC/PAM solution are driven into the reaction tank. The PAC and PAM solution can be adjusted by fuzzy control, so that the phosphates in sewage water can be fully degraded. After the sewage water reacts fully with the reaction liquid, it enters the flocculation tank, and then self-flows into the primary and secondary depositing tanks. In the secondary depositing tank, the sewage water is pumped into the filter by a lifting pump. The filtered water flows into the clean water tank. Then, measure the total phosphates and SS value again, if meet the emission standard, it could be discharged outside.

2 Fuzzy control system for phosphate wastewater treatment .

Because the content of phosphates in sewage water is related to the sewage quantity, season and weather, the phosphates removal process has the features of nonlinearity, time-varying and time lag[Orta-Ledesma MT. 2018, Ramsay IR. & Pullammanappallil PC. 2001], therefore, it is impossible to establish an accurate mathematical model. However, the usual PLC controller is sensitive to the variation of parameters and has great limitations on the improvement of the sewage water treatment control effect[Scherholz ML. & Curtis WR. 2013]. Fuzzy control system is to simulate the actual experience of human beings, without the need of accurate mathematical model, and the control performance is not sensitive to the variation of the parameters. Therefore, Combining fuzzy control technology with PLC control system can improve the reliability and stability of phosphate wastewater treatment system and save the PAC /PAM usage in the phosphates removal process.

2.1 Fuzzy Control Principle

Fuzzy automatic control is a kind of computer digital control system based on fuzzy set theory, fuzzy language variables and fuzzy logic reasoning. It does not depend on the accurate mathematical model of the control system, but depends on the operator's site experience and knowledge to be converted into "fuzzy rules ". Usually a fuzzy controller consists of control rule database, fuzzy input, fuzzy inference algorithm and output clarity[Thi Mai D, Kunacheva C. & Stuckey D. 2018]. Fig. 2 shows the composition of the fuzzy controller.

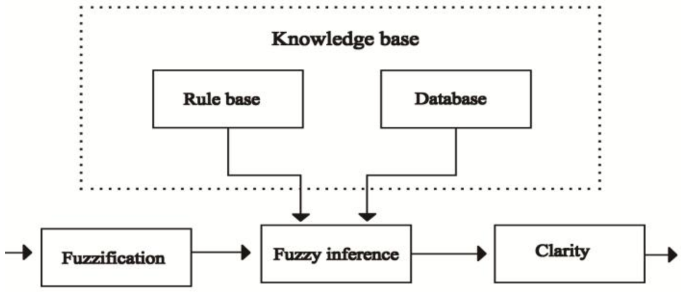

Fig. 2 Fuzzy control model

The quality of constructing a fuzzy control system mainly lies in the design of fuzzy controller[Huang Chao, et al. 2019]. Whereas the performance of a fuzzy controller is determined by fuzzy rules, fuzzy inference algorithm and fuzzy decision, etc.

2.2 Realization of Fuzzy Control

Usually, fuzzy controllers can be classified as simple single input and output, dual input-single output, multi-input and single output, multi-input and multi-output complex

control systems. The control system in this paper was designed as multi-input and multi-output fuzzy controller.

The main purpose of phosphate wastewater treatment control system is to ensure the proper dosage of flocculant (PAC) and coagulant (PAM) in phosphates removal process. Firstly, the content of total phosphates and SS(suspended pollutants) in sewage is detected. Then, the frequency of the output converter is controlled by the fuzzy controller, and the metering pump is driven to realize the precise input of the two kinds of medicament (PAC、PAM) to ensure the best sewage water treatment. The total phosphates(TP) and SS(suspended pollutants) were detected by the total phosphate on-line monitor and SS detector respectively. The system structure of the fuzzy controller for this system can be seen in Fig. 3[Wang Minlin, Liu Zaiwen. 2013].

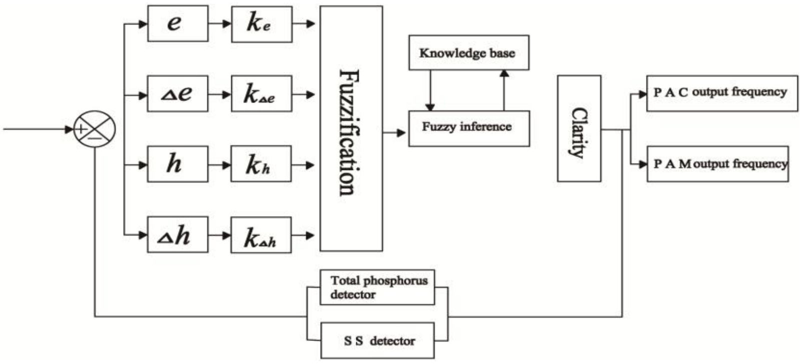

Fig. 3 Fuzzy control system structure

According to the real-time total phosphates and SS contents monitored in sewage water, the output frequency of the converter is compared with the initial setting values, so as to realize real-time control[Wang Minlin, Liu Zaiwen. 2013], In Fig.3, e is input deviation of total phosphates, Δe is variation rate of input deviation of the total phosphates, K_e is input deviation quantization factor of the total phosphates, *h* is input deviation of the SS, Δ*h* is SS input deviation variation rate, $K\Delta_h$ is SS input deviation quantization factor. Through comparison and adjustment, the output frequency of PAC、PAM could be determined[Thi Mai D, Kunacheva C. & Stuckey D. 2018].

2.3 Quantification of inputs and outputs

According to the actual situation, the fuzzy domain of variables is determined. There are four input variables, i.e., the total phosphates input deviation rate e, the total phosphates input deviation variation Δe , the SS input deviation h, the SS input deviation variation rate Δh. There are two outputs, i.e. the PAC output inverter U_1 and the PAM output inverter U_2. The total phosphates and SS input deviation could be classified by using 7 fuzzy subsets, i.e. negative values high (NB), negative values medium (NM), negative values low (NS), moderate values (ZE), positive values small (PS), positive values medium (PM), positive values high (PB). The discrete domain after corresponding quantization is {-3，-2，-1，0，1，2，3}. Total phosphates input deviation variation rate Δe and the SS input deviation variation rate Δ*h* can also classified by using 7 fuzzy subsets, that is, negative values large (NB), negative values medium (NM), negative values low (NS), moderate values (ZE), positive values small (PS), positive values medium (PM), positive values large (PB). The discrete domain after corresponding quantization is {-3，-2，-1，0，1，2，3}. The output frequency fuzzy subsets U_1、U_2 from two inverters can be classified as moderate (ZE), positive small

(PS), positive medium (PM), positive large (PB), which can be classified by using four fuzzy subsets. The discrete domain after corresponding quantization is {0，1，2，3}.
According to the sewage treatment plant records in recent years and the experience analysis, it can be concluded that, the range of total sewage phosphates is [0-10]*mg/l,* the initial given value is 5*mg/l*， then, the input deviation e of the total phosphates is [-5，5]*mg/l*， the basic domain of variation rate Δe of the input deviation of total phosphates is [-0.2，0.2], the domain of SS is [0-1000]*mg/l*，the initial given value is 500*mg/l*，then the physical domain of the input deviation *e* of SS is [-500，500]*mg/l*， The basic domain of the variation rate Δh of input deviation of SS is [-1，1]. The fuzzy domain of 4 input variables is [-3，3], the physical domain of 2 output inverters is [0,50]*Hz*, the fuzzy domain is [0，3], then, the quantization factors are K_e、$K_{\Delta e}$、K_h、$K_{\Delta h}$ respectively;

$$K_e = \frac{3}{5} \quad (1)$$

$$K_{\Delta e} = \frac{3}{0.2} = 15 \quad (2)$$

$$K_h = \frac{3}{500} \quad (3)$$

$$K_{\Delta h} = \frac{3}{1} = 3 \quad (4)$$

A proportional factor of output value $U_1$and U_2 is,

$$K_{U1} = \frac{50}{3} \quad (5)$$

$$K_{U2} = \frac{50}{3} \quad (6)$$

2.4 Determination of Fuzzy Rules

According to the requirement, trigonometric function was selected for the membership function of fuzzy subset. When *e* is positive large(PB), the relevant PAC solution output frequency U_1 is moderate(ZE). When *e* is moderate(ZE), the total phosphates input value deviation variation rate Δe is used to control the PAC solution output frequency. If Δe is positive, there exists an increasing trend, therefore, PAC solution output frequency U_1 takes positive median (PM). When Δe is negative, it shows that there is a decreasing trend, so the output frequency of the PAC solution U_1 takes positive small (PS). Similarly, the fuzzy relationship among the input deviation *h* of SS、deviation variation rate Δh and the output frequency U_2 of PAM solution can be obtained. When h is positive large (PB), the output frequency of the corresponding PAM solution U_2 is moderate (ZE). When the *h* is moderate (ZE), the output frequency of PAM solution can be controlled by the deviation variation rate(Δe) of total phosphates input volume. When the Δh is positive, it shows that there is an increasing trend, so that the output frequency (U_2) of PAM solution takes positive median (PM). When the Δh is negative, it shows that there is a decreasing trend, so that the output frequency (U_2)of the PAM solution takes positive small (PS).
Fuzzy control rules should be described using human experience. For example, if total phosphates input deviation is NB and total phosphates input deviation variation rate is NB, SS input deviation is NB and SS input deviation variation rate is NB, then PAC solution output frequency is NS, and PAM solution output frequency is NS. The meaning of this fuzzy rule

statement is that if the input deviation and the input deviation variation rate of the total phosphates are minimal, and the SS input deviation and the input deviation variation rate are minimal, then, PAC solution output frequency and PAM solution output frequency are moderate.

According to the characteristics of fuzzy control system and statement rules, the corresponding control rules can be obtained, as shown in Table 1 and Table 2.

Table 1 PAC inverter output control rules

The deviation variation rate of TP Δe,	The deviation of TP ,e						
	PB	PM	PS	ZE	NS	NM	NB
PB	ZE	ZE	PS	PS	PM	PM	PM
PM	ZE	ZE	PS	PS	PM	PM	PM
PS	ZE	ZE	PS	PS	PM	PM	PM
ZE	ZE	ZE	PS	PS	PM	PM	PM
NS	ZE	ZE	PS	PM	PM	PM	PB
NM	ZE	ZE	PS	PM	PM	PB	PB
NB	ZE	ZE	PS	PM	PB	PB	PB

Table2 PAM inverter output control rules

The deviation variation rate of SS Δh,	The deviation of SS ,h						
	PB	PM	PS	ZE	NS	NM	NB
PB	ZE	ZE	PS	PS	PM	PS	PM
PM	ZE	ZE	PS	PS	PM	PM	PM
PS	ZE	ZE	PS	PS	PM	PM	PM
ZE	ZE	ZE	PS	PS	PM	PM	PM
NS	ZE	ZE	PS	PM	PM	PM	PB
NM	ZE	ZE	PS	PM	PM	PB	PB
NB	ZE	ZE	PS	PM	PB	PB	PB

3 Design of Fuzzy Controller

Based on FIS System（Fuzzy Inference System）in Matlab, the membership function rules were compiled, see Fig.4 and Fig.5. From the characteristic surface in the FIS, we can directly see the relation between input and output signal, see Fig.6 and Fig7.

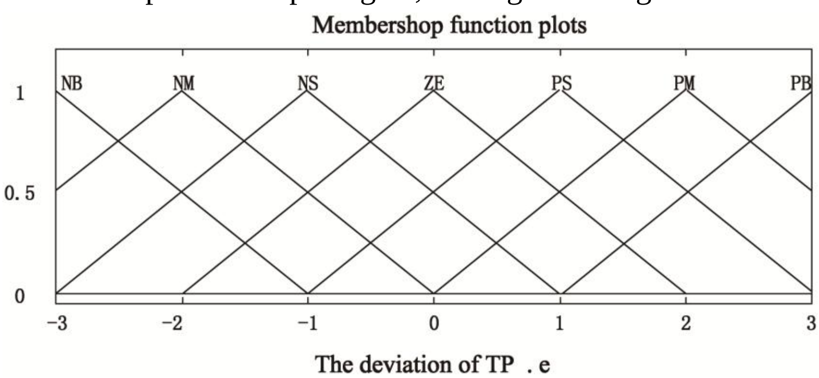

Fig. 4 Membership function of total phosphates deviation, total phosphates deviation variation rate, SS deviation, SS deviation variation rate.

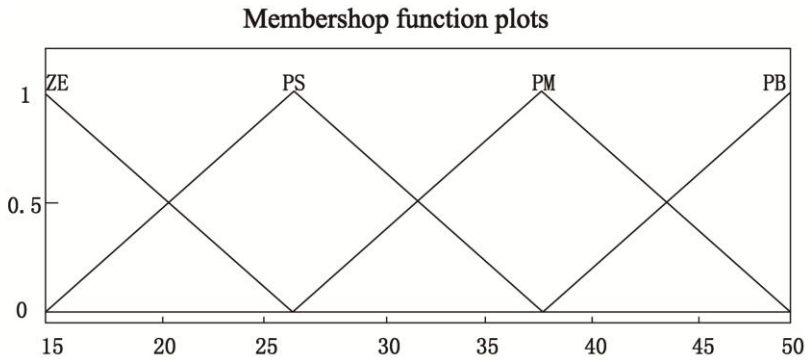

Fig. 5 PAC inverter, PAM inverter membership function

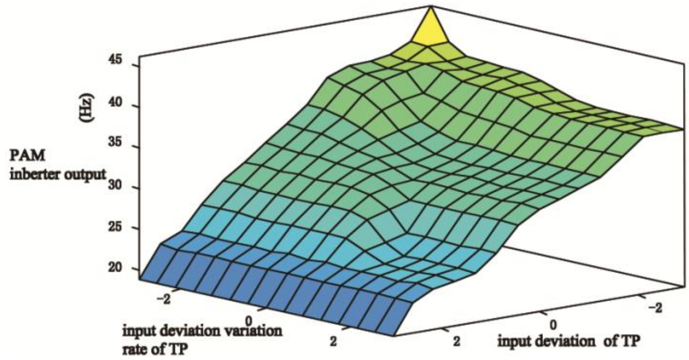

Fig. 6 PAC solution inverter output characteristic surface

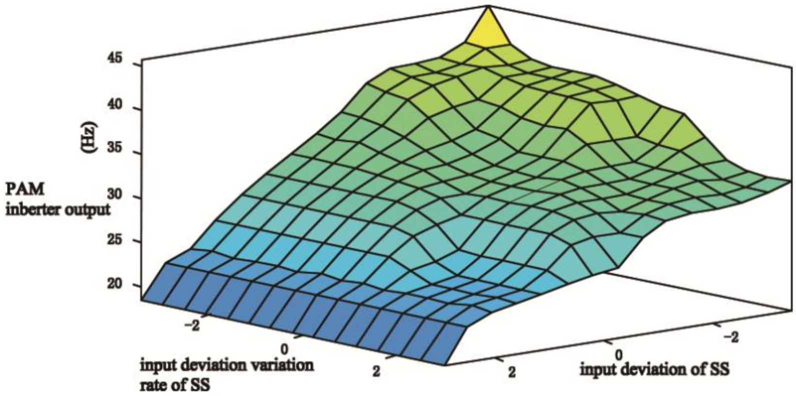

Fig. 7 The output characteristic surface of the PAM solution

4 TP and SS Regulation Process

PAC, chemical formula $[Al_2(OH)_nCl6\text{-}n]$, is an inorganic polymer coagulant. The purpose of phosphates removal is to remove PO_4^{3-} ions from wastewater, in which, Al^{3+} ions in PAC agents could react with PO_4^{3}- to form $AlPO_4$↓ and deposit down. The deposition materials could become sludge and then be treated. PAC chemical equation of phosphates removal is as follows,

$$Al^{3+} + H_nPO_4^{(3-n)-} = AlPO_4 \downarrow + nH^+ \qquad (7)$$

In which, The Molar mass ratio (K) of Al^{3+} ion to P^{5+} ion in sewage water is ,

$$K = T_{Al} / T_P \approx 0.87 \qquad (8)$$

That is ,0.87 mol aluminum can consume 1 mol of phosphates. The PAC inputting process can

be considered as a chemical reaction equation, in which, the output total phosphates P_{out} should be controlled below 0.2 mg/l according to the operation rules(the defined water discharged standard is 0.2 mg/l or less). The total phosphates content discharged is equal to the total phosphates content of sewage influent minus the amount of reaction after inputting PAC medicament, the mathematical model is as follows,

$$P_{out}q_s = P_{in}q_c - 0.87q_j N \quad (9)$$

In which, P_{out} is the total phosphates output value, *mg/l*; P_{in} is input value of the total phosphates in sewage water, *mg/l*; q_s is the instantaneous outflow, l/s; q_c is the instantaneous inflow, *l/s*; q_j is the instantaneous flow of PAC solution, *l/s*; N is concentration of PAC medicament, *g/m*³ During the process of regulation, the frequency of converter is regulated based on fuzzy control principle, and the output flow of PAC solution is adjusted to make the discharged sewage reach the prescribed standard, the relationship between frequency and output flow is as follows,

$$n = 60f / p \quad (10)$$

The above formula is the relation between the working frequency and the working speed of the motor, in which, n is motor speed, *r/min*; f is working frequency of the motor, *Hz*; p is preferable to the extreme logarithm of the motor, which could be taken as 1.

$$q_j = V \times n \times \eta v \quad (11)$$

The above formula is the relationship between the actual speed and the actual flow rate of the pump, in which, q_j is the pump actual outflow, *l/s*; V is pump discharge volume, *l/r*; n is actual pump speed, *r/min*; η_v is pump capacity efficiency,

Combination of formulas above, it could be obtained the following TP regulation formula,

$$p_{out}q_s = p_{in}q_c - 0.87V \times 60f / p \times \eta v N \quad (12)$$

According to the actual pump , η_v is taken as 0.98.

There is no accurate mathematical model for the adjustment process of SS (suspended pollutants). When the SS value in the sewage inflow becomes larger, the output frequency value of PAM solution is adjusted accordingly.

5 Simulation Test

5.1 Simulation analysis

In order to verify the performance and practicability of the designed fuzzy controller, the PAC solution output system is simulated and analyzed according to the mathematical model (12). For the fuzzy control system constructed in this paper, the concentration (N) of PAC is 5%, the total phosphates (TP) of sewage water inflow is 4.6 *mg/l*; the instantaneous inflow of sewage water is 45 *l/s*; q_s is the instantaneous outflow, 45*l/s*. According to the discharge requirement, the total phosphates outflow (P_{out}) is 0.2 *mg/l*.

According to the PAC inflow process, the transfer function is a higher order transfer function with delay link. After simplification, is can be obtained,

$$G(S) = \frac{-0.11e^{-3s}}{(13.8s+1)^5} \quad (13)$$

Based on the Matlab and Simulink module, the fuzzy control system in this paper can be modeled and simulated, as shown in Fig. 8 and Fig. 9.

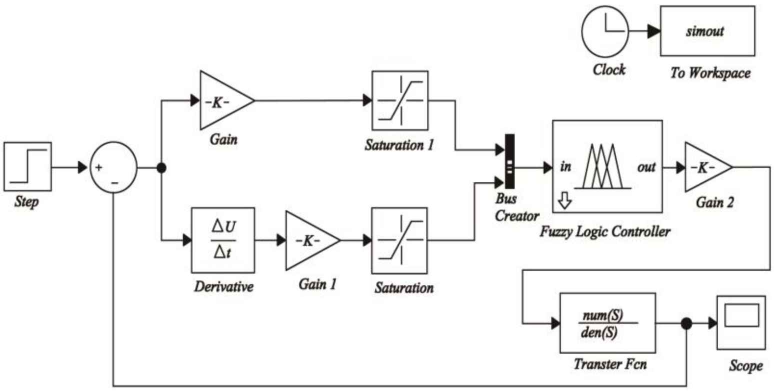

Fig. 8 Fuzzy control model

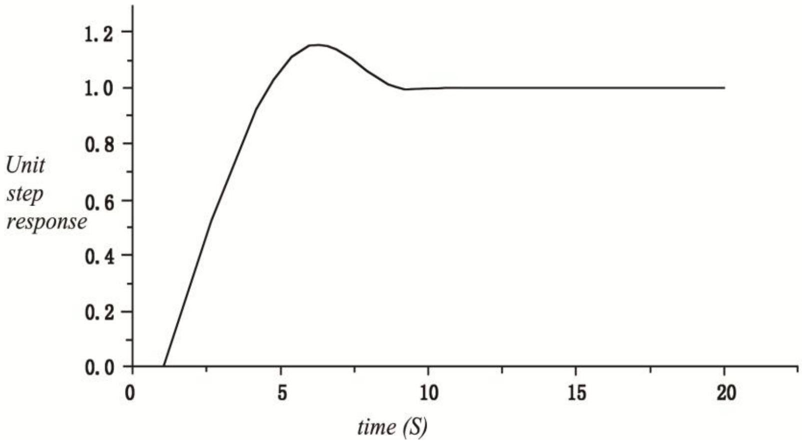

Fig. 9 Unit step response curve of fuzzy control model

5.2 Experiment verification

A fuzzy control model designed in this paper is input into the PLC control system. According to operation and regulation, the diagram of sewage water inflow and outflow can be constructed as Fig.10 and Fig.11.

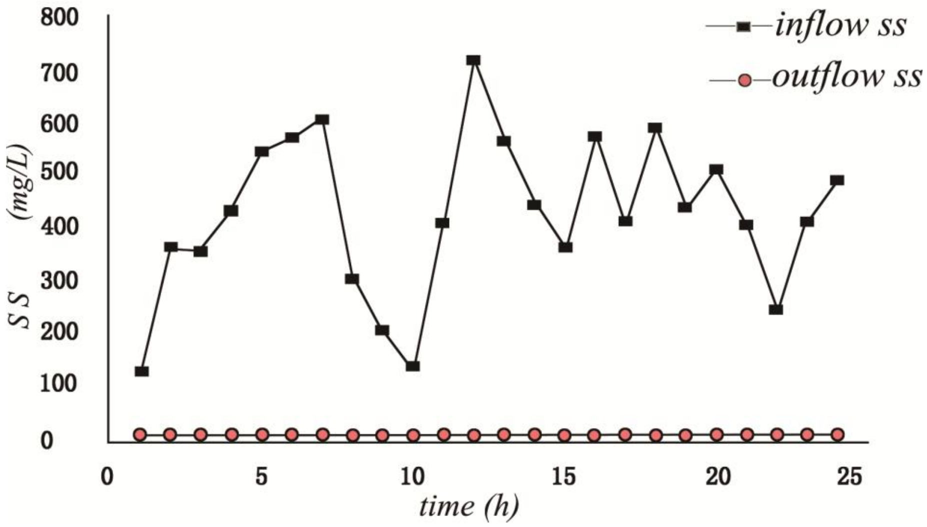

Fig. 10 Comparison of SS (suspended matter) value before and after

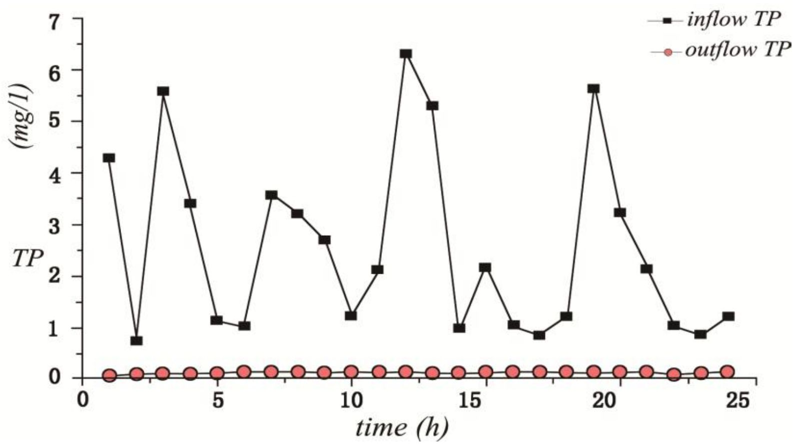

Fig. 11 Comparison of total phosphorus value before and after

It can be seen from the above figures that variation amplitude of inflow TP and SS is large, whereas the TP and SS in the outflow are below 0.2 mg/l、50mg/l respectively, which reaches the discharged standard. and the TP and SS in the outflow are stable and all below the relevant standard. Compared with the condition of no fuzzy control model, the dosage of PAC and PAM are reduced by about 1/3.

6 Conclusions

It can be seen from the above fuzzy simulation control model that the unit step response regulation is small, the control process has no oscillation phenomenon, and the state of stability is maintained.

Compared with the traditional PLC control model, which is sensitive to parameter variation and unstable, the fuzzy control model designed in this paper can make the whole control system more stable, less regulation and faster time response.

Based on the combination of PLC and fuzzy control, it is concluded from site experiment that the stability of the control system is improved by adding fuzzy control method. It can meet the requirements of phosphates removal in phosphate wastewater treatment, save the sewage treatment agents and make the whole system more economical. The results show that it is feasible and effective to apply fuzzy control technology to phosphates removal control system in phosphate wastewater.

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Declaration of Competing Interest

The author declare that there should be no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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