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THE IMMUNE FUZZY PID STRIPPER TEMPERATURE CONTROL ALGORITHM BASED ON CHAOTIC OPTIMIZATION

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Abstract. *Polyvinyl chloride (PVC) stripping process has characteristics of being highly nonlinear, large time delay and the temperature being difficult to control precisely. Immune fuzzy PID controller was adopted to control the stripping temperature, and chaos optimization algorithm is proposed for parameter optimization of fuzzy immune PID controller. Firstly, through the chaotic coarse search (once carrier), the sub-optimal solution of parameters can be obtained quickly. Secondly, the fine search (secondary carrier) is used to find out the global optimal values in the near-field of sub-optimal solution. Finally, the new control system is simulated and compared with the conventional PID controller, fuzzy PID controller and immune fuzzy PID controller. The simulation results show that the chaotic optimization-immune fuzzy PID controller has the smaller overshoot, shorter settling time and faster response speed, and that the control effect of the stripping tower is obviously improved.*

Keywords: Stripper temperature, Chaotic optimization, Immune theory, Fuzzy control, PID

1. **Introduction.** Polyvinyl chloride (PVC) as the world's second-largest general resin, has extensive applications. Vinyl chloride monomer (VCM) is the main raw material for the synthesis of polyvinyl chloride, which has certain toxicity. In industrial production, the stripper tower is used to prolapse the excess VCM in PVC product, and control the VCM content of PVC product within the standard range. Therefore, using the advanced control algorithm to improve the quality of PVC product, control the VCM content, reduce the costs of production and protect the environment has become a new research project [1-3].

Chaotic phenomena are spread widely in nonlinear systems, which is not a mess, but there is a phenomenon of the inevitable inner link. In [4], chaotic control is used to eliminate the phenomenon of chaos, the controllability and stability of the time-delayed feedback control is effectively verified, so in recent years chaos control and chaos optimization algorithm is becoming a hot research topic. In [5], Wu et al. used chaotic optimization PID parameters control algorithm to apply to the hydraulic driving system, and the simulation results show that it has good dynamic and static performance. In [6], Zou et al. designed an optimal fuzzy PID controller and introduced chaotic optimization algorithm, and the results prove the system has the small overshot fast response. In [7] chaotic optimization and immune PID controller are combined, and the results show that the chaotic optimization combined with other algorithms achieved good control effect. In [8], the fuzzy immune PID controller is applied to the fractionating tower control system. [9] proposed fuzzy immune PID controller that is applied to the resin crystalline kettle temperature control. The objects in [8] and [9] are similar to the PVC stripper process, but how to get parameters more quickly and accurately is inadequate.

So in this paper, according to the fact that the Polyvinyl chloride (PVC) stripping process has characteristics of being highly nonlinear, large time delay and the temperature being difficult to control precisely, chaos optimization control algorithm is proposed, and applied to the stripping temperature control of the immune fuzzy PID. Firstly, through the chaotic coarse search (once carrier), obtain the sub-optimal solution of parameters quickly. Secondly, the fine search (secondary carrier) is used to find out the global optimal values in the near-field of sub-optimal solution. Finally, the new control system is simulated and compared with the conventional PID controller, fuzzy PID controller and immune fuzzy PID controller. The simulation results show that this method has smaller overshoot, faster response speed, improving the dynamic and static performance. So this control algorithm applied to the stripping temperature control is feasible and effective, and it can make the system's overshoot smaller, as soon as possible to achieve stability.

The rest of the paper is organized as follows. Section 2 proposes the immune mechanism and then a design for immune fuzzy PID controller is given. Chaos optimization algorithm is presented in Section 3. Simulation study is made in Section 4, and compared with other methods. Finally, conclusions and some remarks are given in Section 5.

2. **Design for Immune Fuzzy PID Controller.** Biological immune system is a complex system which includes lymphocytes and antibody molecules. T cells and B cells form lymphocytes, T cells differentiate into T_H cells (named helper T-cells) and T_S cells (named suppressor T-cells) by antigen stimulus. T_H cells could promote the production of B cells, T_S cells could inhibit the production of B cells. Both the T_H cells and T_S cells stimulate B cells to produce antibodies to destroy the antigen. T cells and B cells work together to maintain the balance of the body immune system. The basic configuration diagram of a biological immune system is in Figure 1.

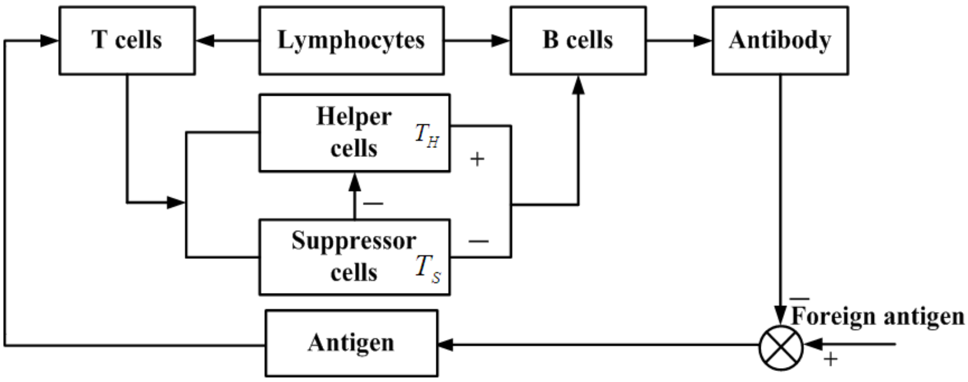

FIGURE 1. Biological immune system diagram

Suppose the number of the k antigen is $\alpha(k)$, the number of T_H cells is $T_H(k)$, then,

$$T_H(k) = k_1\alpha(k) \tag{1}$$

where k_1 is the positive factor.

Due to the fact that the T_S cells could affect the production of B cells, assuming the effect of T_S cells to B cells is $T_S(k)$, then,

$$T_S(k) = k_2 f(\Delta s(k))\alpha(k) \tag{2}$$

where k_2 is an inhibitory factor and its symbol is positive. $f(*)$ is a nonlinear function, which represents the inhibition amount of T_S cells. The output of $f(*)$ is limited to $[0, 1]$.

By Equations (1) and (2), then the total stimulation received by B cells was:

$$S(k) = T_H(k) - T_S(k) = (k_1 - k_2 f(\Delta s(k)))\alpha(k) \quad (3)$$

This is an immune feedback control [10].

The discrete form of common PID controller is:

$$u_{PID}(k) = u(k-1) + K_P(e(k) - e(k-1)) + K_I e(k) + K_D(e(k) - 2e(k-1) + e(k-2)) \quad (4)$$

From Equation (4), the control type of P controller is:

$$u(k) = K_P e(k) \quad (5)$$

where assume $\alpha(k)$ as the system deviation $e(k)$, $S(k)$ as the system output $u(k)$, by Equation (3):

$$u(k) = K(1 - \eta f(u(k), \Delta u(k)))e(k) = K_{P1}e(k) \quad (6)$$

where $K_{P1} = K(1 - \eta f(u(k), \Delta u(k)))$, $K = k_1$ is control reaction rate, if k_1 increases, it can improve the response speed. $\eta = k_2/k_1$ is control-stability effect, and if η increases, it can reduce the overshoot and improve the stability.

By Equations (4), (5) and (6), the output of immune PID controller is [11]:

$$u(k) = u(k-1) + K_{P1}(e(k) - e(k-1)) + K_I' e(k) + K_D'(e(k) - 2e(k-1) + e(k-2)) \quad (7)$$

The block diagram of the immune fuzzy PID stripping temperature control system is shown in Figure 2.

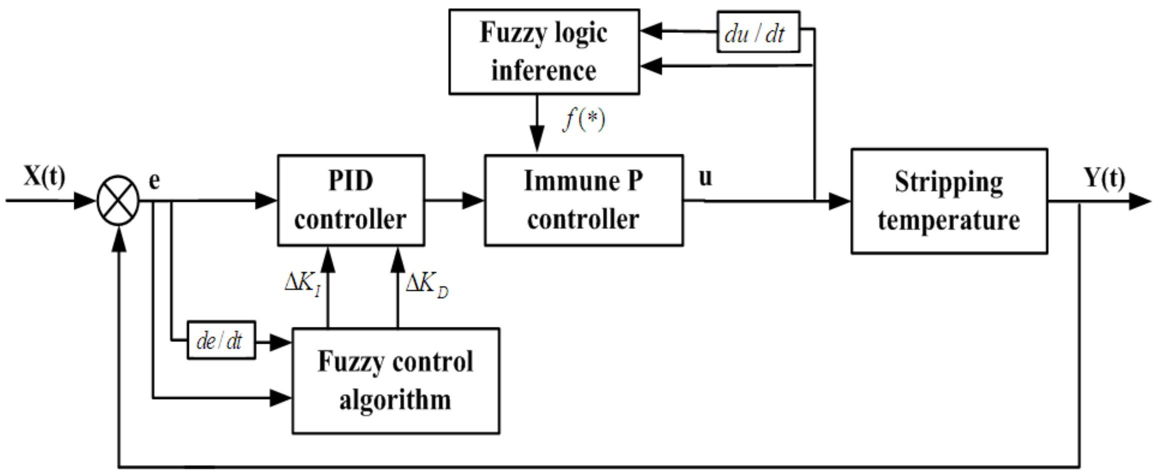

Figure 2. The block diagram of the immune fuzzy PID stripping temperature control system

By Equations (6) and (7), the selection of $f(*)$ is the key. In this paper, the principle of fuzzy control system approximate nonlinear function is used to select the nonlinear function $f(*)$. The type is double inputs and single output. The inputs are $u(k)$ and $\Delta u(k)$, and the output is $f(u(k), \Delta u(k))$. The input variables are fuzzed by 2 fuzzy sets, which are named "Positive" (P) and "Negative" (N), and the output variable is fuzzed by 3 fuzzy sets, which are named "Positive" (P), "Negative" (N) and "Zero" (Z). Membership functions are shown in Figure 3 and Figure 4.

Fuzzy inference rules are derived by Lyapunov synthesis method to ensure $f(*)$ on the stability of the system [12]. The fuzzy rules are shown in Table 1.

The fuzzy rule of $f(*)$ is using AND operation of Zadeh method and the weighted average fuzzy method is used to obtain output $f(*)$.

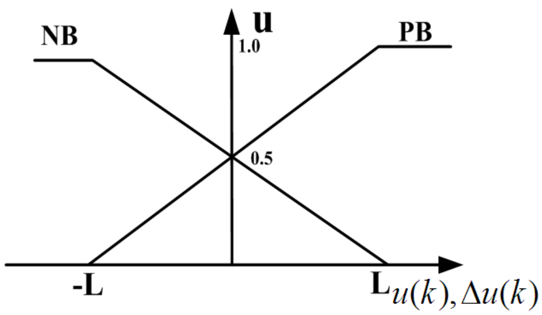

FIGURE 3. The membership functions of inputs

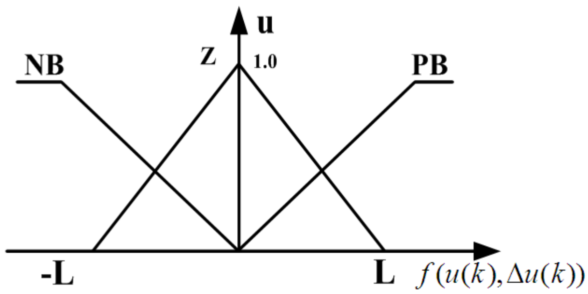

FIGURE 4. The membership function of output

TABLE 1. The fuzzy rule of $f(*)$

$u(k)(x_1)$	$\Delta u(k)(x_2)$	
	P	N
P	N	Z
N	Z	P

TABLE 2. The membership functions table of e and ec

e	-1	-0.75	-0.5	-0.25	0	0.25	0.5	0.75	1
PB	0	0	0	0	0	0.1	0.4	0.7	1.0
PM	0	0	0	0	0.1	0.4	0.7	1.0	0
PS	0	0	0	0.1	0.4	0.7	1.0	0	0
Z	0	0.1	0.4	0.7	1.0	0	0	0	0
NS	0.1	0.4	0.7	1.0	0	0	0	0	0
NM	0.4	0.7	1.0	0	0	0	0	0	0
NB	1.0	0	0	0	0	0	0	0	0

Fuzzy inference system is shown in Figure 2. It is a two-dimensional fuzzy controller. The inputs error is e and the ec is the error changed rate; the outputs are ΔK_I and ΔK_D. The fluctuation of e is $(-1 \sim 1)$°C and ec is $(-1 \sim 1)$°C$/h$, according to the input membership functions curve in Figure 3, the membership functions table of e and ec is obtained in Table 2. And the domain of ΔK_I and ΔK_D are defined as $(-1.0, -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1.0)$; the fuzzy control rule table of ΔK_I and ΔK_D is shown in Table 3 [13-15].

3. **Chaotic Optimization Algorithm.** According to the chaotic motion with ergodicity, stochastic property, and regularity of chaotic, the chaotic optimization algorithm is

TABLE 3. The fuzzy control rules of ΔK_I and ΔK_D

ec	*e*						
	PB	PM	PS	Z	NS	NM	NB
PB	1.0	0.9	0.8	0.6	0.2	0	0
PM	0.9	0.7	0.6	0.4	0.2	0	0
PS	0.6	0.4	0.2	0.1	0	−0.1	−0.2
Z	0.4	0.3	0.1	0	−0.1	−0.2	−0.4
NS	0.2	0.1	0	−0.1	−0.2	−0.4	−0.6
NM	0.1	0	−0.1	−0.2	−0.4	−0.6	−0.9
NB	0	−0.1	−0.2	−0.4	−0.6	−0.9	−1.0

proposed. By Equation (6), the performance of the controller is determined by the choice of the three parameters of $K_p' = K(1 - \eta f(u(k), \Delta u(k)))$, k_i' and k_d'. So, if the chaotic optimization is applied to optimize the parameters, it will be more advantageous than the general parameters debugging.

The basic steps of chaotic optimization algorithm are as follows.

K_p' could be set to K and η. So, in order to get the optimal values of K, η, k_i', k_d', through the coarse search (once carrier), the suboptimal values can be obtained quickly, then the fine search (secondary carrier) is used to find out the global optimal value in the near-field of suboptimal values.

The 'Logistic' mapping is selected as:

$$X_{n+1} = \mu * X_n(1 - X_n) \tag{8}$$

where μ is the control parameter, $n = 1, 2, \cdots$. And when $\mu = 4$ and $X_n \in (0, 1)$, the logistic map is completely in chaos state. By using the characteristic that the chaotic state is sensitive to initial value, taking i initial values can get the same number, different trajectories of chaotic variables.

Above of all, the chaotic variables of K, η, k_i' and k_d' respectively represent $X_{1,n+1}$, $X_{2,n+1}$, $X_{3,n+1}$, $X_{4,n+1}$. Because the range of the chaotic variables is limited at $(0, 1)$, the optimal variables of K, η, k_i' and k_d' are $X'_{1,n+1}$, $X'_{2,n+1}$, $X'_{3,n+1}$, $X'_{4,n+1}$. Then, the range of the chaotic variables is adjusted to the range of optimal variables:

$$\begin{aligned} X'_{1,n+1} &= a_1 + b_1 X_{1,n+1} \\ X'_{2,n+1} &= a_2 + b_2 X_{2,n+1} \\ X'_{3,n+1} &= a_3 + b_3 X_{3,n+1} \\ X'_{4,n+1} &= a_4 + b_4 X_{4,n+1} \end{aligned} \tag{9}$$

in which a_i and b_i are constants and they are named for 'adjust' factors.

Through adjusting the control object by each value of $X'_{1,n+1}$, $X'_{2,n+1}$, $X'_{3,n+1}$ and $X'_{4,n+1}$, draw the output value. In w times, find out the value to meet the performance index of ITAE. In this paper, the performance index of ITAE reference is from [16]:

$$J(ITAE) = \int_0^T t|e(t)|dt \longrightarrow \min J \tag{10}$$

Then, $x_1(k) = \left(X'_{1,n+1}, X'_{2,n+1}, X'_{3,n+1}, X'_{4,n+1}\right)$, calculate the performance index of $f_1(k)$. Given the initial value: $f* = f(0)$. If $f_1(k) \le f*$, then $f* = f_1(k)$. Else give up $x_1(k)$, $k = k + 1$. When $f*$ unchanged, select the values of $X'_{1,n+1}$, $X'_{2,n+1}$, $X'_{3,n+1}$ and $X'_{4,n+1}$ respectively as the four sub-optimal values of K^*, η^*, $k_i'^*$ and $k_d'^*$ of the immune fuzzy PID controller. Above is the coarse search process of chaotic optimization.

On the basis of the sub-optimal values, reduce the traverse region of chaotic variables, and conduct secondary carrier. According to 'Logistic' mapping:

$$\begin{aligned} K_{1,n+1} &= K^* + c_t X_{1,n+1} \\ \eta_{1,n+1} &= \eta^* + c_t X_{2,n+1} \\ k'_{i1,n+1} &= k'^*_i + c_t X_{3,n+1} \\ k'_{d1,n+1} &= k'^*_d + c_t X_{4,n+1} \end{aligned} \tag{11}$$

$$c_{t+1} = (1 - \delta) * c_t \quad (0 < \delta < 1) \tag{12}$$

in which c_t is time-varying parameter, and δ is decay factor. The effect of δ is to reduce the traverse region of chaotic variables. It is terminated when meeting $c_{t+1} \le R$ (R is a constant value that is given), otherwise will search again. In this case the result is the global optimal value of K, η, k'_i and k'_d.

In summary, the block diagram of the immune fuzzy PID stripping temperature control system based on chaotic optimization is shown in Figure 5 [17,18].

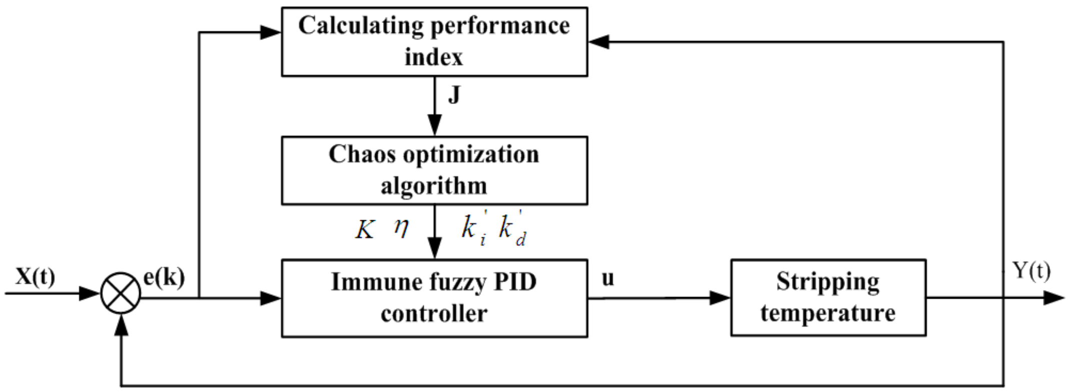

Figure 5. The block diagram of the immune fuzzy PID stripping temperature control system based on chaotic optimization

4. **Simulation Research.** Temperature is a very important factor for PVC stripper process, which directly affects the amount of VCM final residues in PVC resin. When the stripping temperature is higher, the VCM final residues are lower. When the temperature exceeds 95°C, VCM residual amount is reduced, but when the temperature is too high, it will make the PVC decompose, thus affecting the quality of the PVC production. So, the top of stripping temperature is controlled in 100 ± 1°C [19].

According to the temperature model and control condition of PVC stripping process, in this paper, the conventional PID algorithm, fuzzy PID algorithm, immune fuzzy PID algorithm and chaotic optimization-immune fuzzy PID algorithm are simulated and compared separately. In the operation process of stripper tower, the external environment will have a greater impact on the system; therefore, a disturbance is added and the temperature setting value is changed. The four kinds of control algorithm simulation results are compared and analyzed, and at last the satisfactory curves are obtained.

According to the Ziegler-Nichols method, and using the boundary stability method, the conventional PID initial parameters are selected as: $K_P = 0.347$, $K_I = 0.038$, $K_D = 0.079$; e and ec are the input variables of fuzzy controller, so the fuzzy PID initial parameters are selected as: $K_{P0} = 0.320$, $K_{I0} = 0.036$, $K_{D0} = 0.083$; according to the experience, the immune fuzzy PID parameters are selected as: $K = 0.310$, $\eta = 1.680$, $K_{I1} = 0.040$, $K_{D1} = 0.080$; the once carrier is used for selecting the parameters of the chaotic optimization-immune fuzzy PID algorithm; the adjustment coefficients are: $a_1 = 0$, $a_2 = 0$, $a_3 = 0$,

$a_4 = 0$, $b_1 = 4$, $b_2 = 1$, $b_3 = 2$, $b_4 = 8$. By Equation (11), the selection of sampling point is 100, namely every 100 steps, search optimal 1 time. The chaotic coarse search times: $w = 2000$. Then, the sub-optimal solutions: $K^* = 0.342$, $\eta^* = 1.725$, $k_i'^* = 0.043$, $k_d'^* = 0.075$. Based on the suboptimal solutions, the second carrier is used. By Equation (12), the time-varying parameter c_t initial value is 0.8, the constant R is 0.001, then the second carrier is over when $c_{t+1} \leq 0.001$. So the global optimal solution is: $K_1 = 0.324$, $\eta_1 = 1.765$, $K_{I2} = 0.052$, $K_{D2} = 0.094$.

(1) When the stripper during normal operation, the four algorithm control curves are shown in Figure 6.

From Figure 6, the overshoot is reduced to 3%, the time to achieve stability is shortened to 180s, and the parameters of immune fuzzy PID controller are optimized by chaotic optimization algorithm.

(2) The distraction of amplitude 8 is put into the stripping process in the 500s, and the comparison of four kinds of control curves is shown in Figure 7.

(3) The setting temperature value is increased from 100°C to 108°C, and four kinds of control curves are shown in Figure 8.

From Figure 8, the control curve of chaotic optimization-immune fuzzy PID controller has faster response, and the ability to adapt is better than other controllers.

The analysis of simulation results is given in Table 4.

It can be seen from Table 4, compared with conventional PID, fuzzy PID, immune fuzzy PID, chaotic optimization-immune fuzzy PID has the smaller overshoot, shorter settling time and faster response speed.

5. **Summary.** For the PVC stripping process characteristics, immune fuzzy PID controller is applied, and chaotic optimization is used to optimize the parameters of immune fuzzy PID controller. Simulation results show that this method has small overshoot,

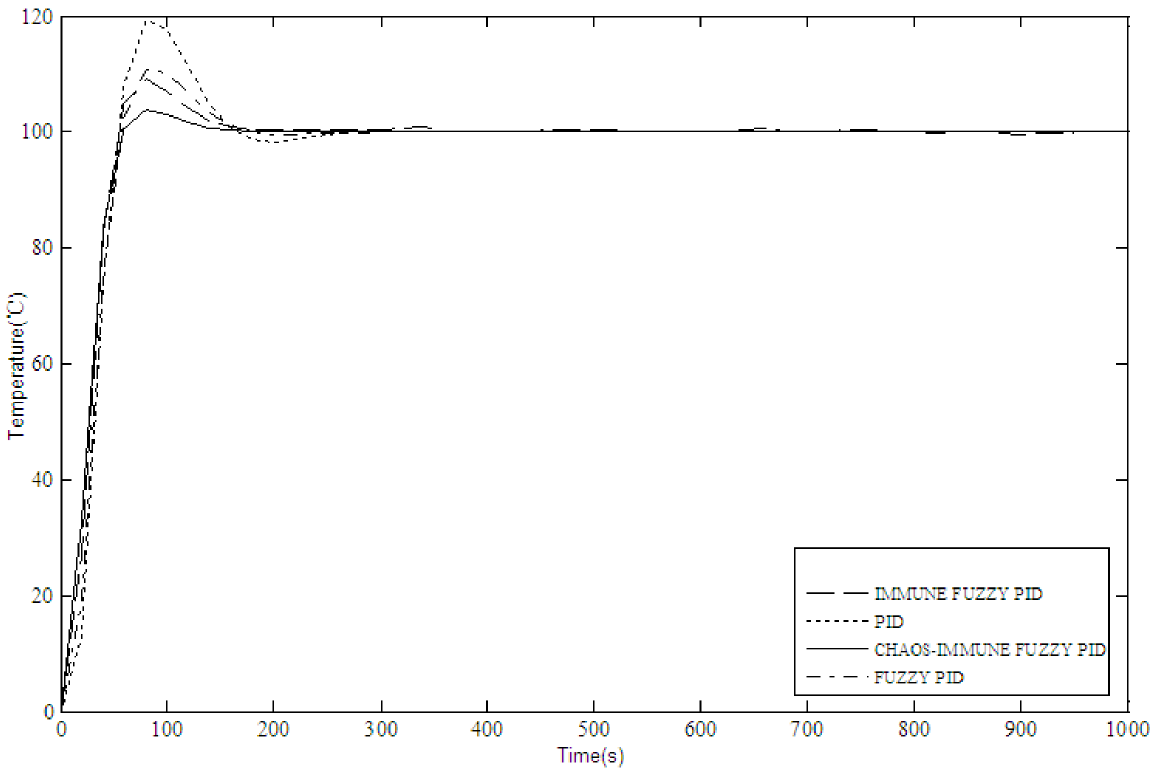

Figure 6. The response curves of the comparison of four kinds of control methods

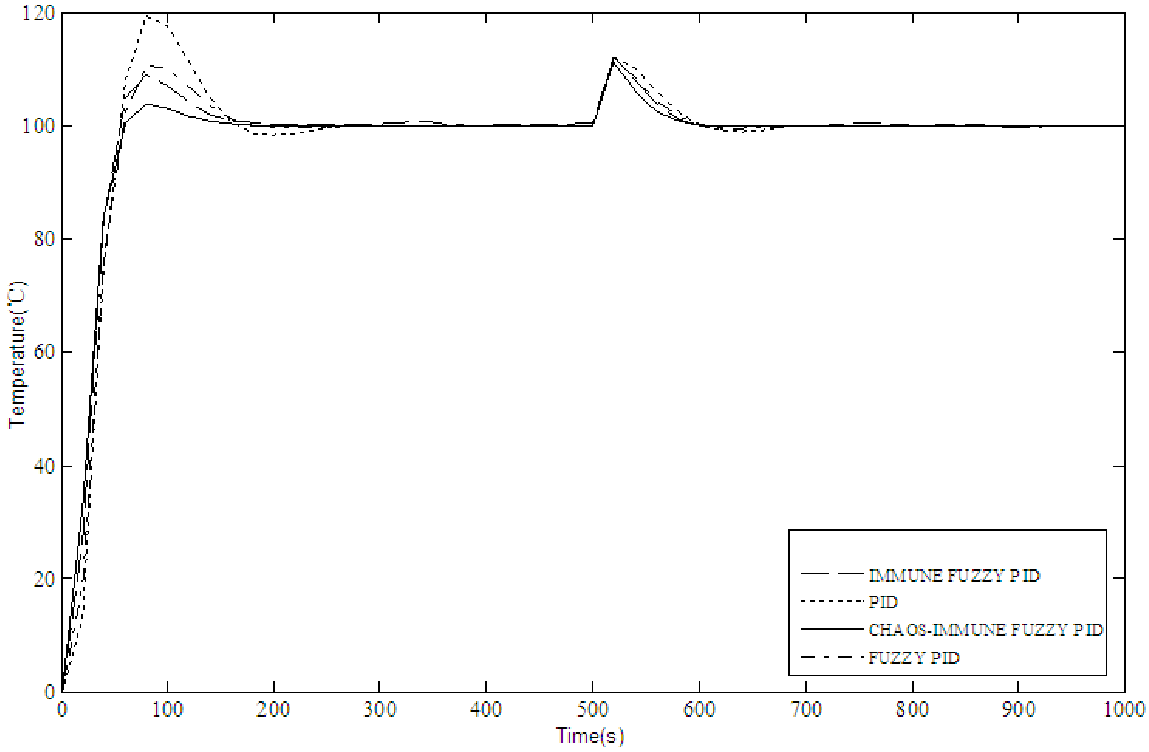

Figure 7. Comparison of response curves under the interference value of 8

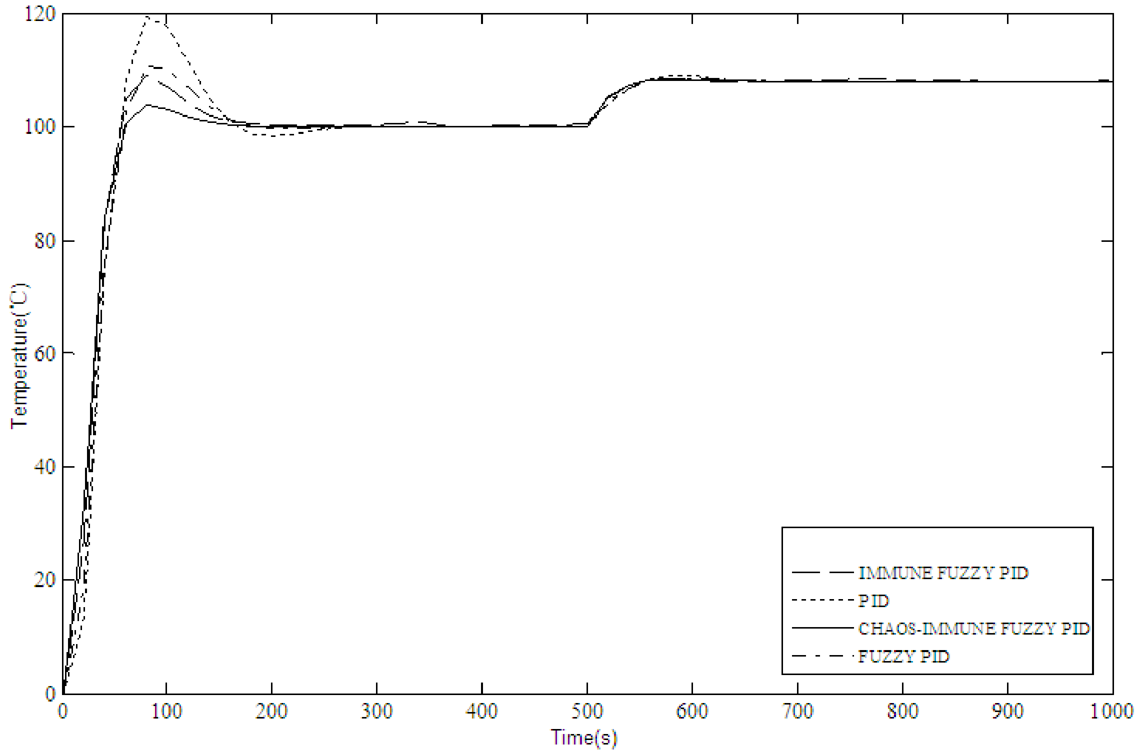

Figure 8. Comparison of response curves when the setting temperature changed

TABLE 4. The simulation analysis and parameters of four controller algorithms

Control algorithm	Parameter selection	Overshoot	To achieve stable time
Conventional PID	$K_P = 0.347$, $K_I = 0.038$, $K_D = 0.079$	19%	360s
Fuzzy PID	$K_{P0} = 0.320$, $K_{I0} = 0.036$, $K_{D0} = 0.083$	12%	280s
Immune fuzzy PID	$K = 0.310$, $\eta = 1.680$, $K_{I1} = 0.040$, $K_{D1} = 0.080$	9%	240s
Immune fuzzy PID based on chaotic optimization	$K_1 = 0.324$, $\eta_1 = 1.765$, $K_{I2} = 0.052$, $K_{D2} = 0.094$	3%	160s

faster response speed, improving the dynamic and static performance. For the control of the stripper temperature more effectively, ensuring the content of VCM in PVC products within the standard range, this control algorithm is feasible and effective. In future research, we will make the chaotic optimization-immune fuzzy PID controller applied to the actual operation of stripper process of the PVC production. In addition, this control algorithm provides an excellent reference for other complex industrial temperature control.

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REFERENCES

[1] X. Wang and Z. Tang, Methods to improve the capacities of converters, *Polyvinyl Chloride*, vol.43, no.6, pp.31-34, 2015.

[2] Z. Zhou, Control system design of PVC stripper, *Manufacturing Automation*, vol.33, no.2, pp.192-194, 2011.

[3] J. Wang, Present conditions and development trends of PVC industry, *Qilu Petrochemical Technology*, vol.39, no.1, pp.77-80, 2011.

[4] C. Xu and Y. Wu, Chaos control of a chemical chaotic system via time-delayed feedback control method, *International Journal of Automation and Computing*, vol.11, no.4, pp.392-398, 2014.

[5] F. Wu, B. Huang and H. Zhou, Research for the hydraulic walking system of the asphalt paver based on chaos optimization of PID parameters, *Journal of Machine Design and Research*, vol.28, no.3, pp.82-84, 2012.

[6] E. Zou, W. Wu, X. Xiang and T. Zhang, A new type chaos optimization design of fuzzy PID controller, *Process Automation Instrumentation*, vol.25, no.12, pp.12-14, 2004.

[7] G. Han, Chaos optimization based immune PID controller design, *Journal of Xi'an University of Telecommunications*, vol.17, no.5, pp.74-77, 2012.

[8] H. Wang, X. Zhang, X. Dong and X. Tian, Design of rectifying tower control system based on fuzzy immune PID and its implementation, *Industry and Mine Automation*, vol.37, no.5, pp.44-48, 2011.

[9] D. Wen, H. Zeng and Y. Li, Research of a new fuzzy-immune-PID on temperature control, *Microcomputer Information*, vol.29, no.11, pp.42-45, 2009.

[10] C. A. Janeway and J. R. R. Medzhitov, Innate immune recognition, *Annual Review of Immunology*, vol.20, pp.197-216, 2002.

[11] Y. Zhu and L. Xu, Application study of fuzzy immune PID algorithm in temperature control system, *Automation & Instrumentation*, vol.8, pp.11-13, 2012.

[12] B. Ren and L. Cheng, The structure of V function in Lyapunov's stableness theory, *Automation and Instrumentation*, vol.2, pp.8-11, 2009.

[13] C. Ken, The quality evaluation method of instrument flight procedure design scheme based on fuzzy linguistic assessments, *Journal of Chemical and Pharmaceutical Research*, vol.5, no.11, pp.12-16, 2013.

[14] C. Xie, H. Bao, J. Du and L. Yan, Application of a new membership function of nonlinear fuzzy PID controller with variable gains, *Information and Control*, vol.43, no.3, pp.264-269, 2014.

[15] Y. Zhao, X. Qu and L. Rui, Self-adjusting control system of temperature based on fuzzy algorithm, *Journal of Tianjin University*, vol.44, no.1, pp.73-78, 2011.

[16] S. Wang and Z. Guo, Novel chaos immune optimization combination algorithm, *Control and Decision*, vol.21, no.2, pp.205-209, 2006.

[17] S. C. Leandro, Tuning of PID controller for an automatic regular voltage system using chaotic optimization approach, *Chaos, Solitons & Fractals*, vol.39, no.4, pp.1504-1514, 2009.

[18] R. Caponetto, L. Fortuna and S. Fazzino, Chaotic sequences to improve the performance of evolutionary algorithms, *IEEE Trans. Evolutionary Computation*, vol.7, no.3, pp.289-304, 2003.

[19] M. Zhang, T. Zhang and X. Peng, Improvements on PVC stripping towers, *Polyvinyl Chloride*, vol.39, no.7, pp.36-39, 2011.