Simulation of Smith fuzzy PID temperature control in enzymatic detection of pesticide residues

Sun Jun*, Zhang Meixia, Li Zhengming, Wu Xiaohong

(*School of Electrical and Information Engineering, Jiangsu University, Zhenjiang 212013, China*)

Abstract: Enzyme activity is easily influenced by temperature, resulting in accuracy decline of enzymatic detection of pesticide residues. In this study, a controller which controls the internal temperature of the pesticide residues detector was simulated and analyzed. The mathematical model of temperature control was established by the application of the heat transfer theory. Against models with characteristics of large inertia and large hysteresis, a Smith fuzzy PID controller was proposed by combining the Smith predictor with the fuzzy PID controller. The PID controller, the fuzzy PID controller, and the Smith fuzzy PID controller were simulated in MATLAB, respectively in the same step signal given with amplitude of 1. The performance indexes (percent overshoot, settling time, and steady-state error) of various controllers were presented as follows: the PID controller (19%, 250 s, 0.0001), the fuzzy PID controller (11%, 450 s, 0.0001), and the Smith fuzzy PID controller (0%, 140 s, 0). From 1 180 s to 1 230 s, an interference signal with amplitude of 5 was added to test interference immunity. The PID controller and the fuzzy PID controller had greater fluctuations, but the Smith fuzzy PID controller had no fluctuations. The recovery time of each controller was described below: the PID controller (200 s), the fuzzy PID controller (300 s), and the Smith fuzzy PID controller (120 s). Robustness of the controller was tested by adjusting the time constant and the delay time. The performance indexes of the controllers were shown as follows: the PID controller (38%, 450 s, 0.0001), the fuzzy PID controller (23%, 880 s, 0.00025), and the Smith fuzzy PID controller (1%, 150 s, 0). The results of simulation showed that the performance indexes of the Smith fuzzy PID controller were better than that of the other controllers. Besides, the robustness and interference immunity are stronger than other controllers as well. The Smith fuzzy PID controller can accurately control the internal temperature of the pesticide residues detector to provide the best temperature for enzymatic detection.

Keywords: enzymatic detection, Fuzzy PID, Smith predictor, simulation, temperature control

DOI: 10.3965/j.ijabe.20150801.007

Citation: Sun J, Zhang M X, Li Z M, Wu X H. Simulation of Smith fuzzy PID temperature control in enzymatic detection of pesticide residues. Int J Agric & Biol Eng, 2015; 8(1): 50－56.

1 Introduction

Due to the extensive use of pesticides, the food chain and environment in a lot of parts of the world have been contaminated. Pesticide residues increasingly endanger human health. Traditional methods to detect pesticide residues include gas chromatography, high performance liquid chromatography, gas chromatography - mass spectrometry, etc. However, these methods with high costs and complicated operation are not suitable for on-site testing. Therefore, to develop a rapid detection method becomes a research hotspot in China and around the world, and the enzymatic inhibition method is the most widely pesticide residue detection technology at present[1-10]. The temperature is an important factor affecting enzyme activity based on the enzyme dynamics analysis system. For example, the activity of

---

Received date: 2014-01-18 **Accepted date:** 2014-11-07

Biographies: Zhang Meixia, Master, research interests: the detection of pesticide residues. Email: 767049680@qq.com. **Li Zhengming**, Professor, research interests: electrification and automation in agricultural engineering. Email: lzming@ujs.edu.cn. **Wu Xiaohong**, PhD, research interests: Applications of signal processing in agricultural engineering. Email: wxh_www@163.com

***Corresponding author: Sun Jun,** PhD, Professor, research interests: Applications of signal processing in agricultural engineering. Mailing address: No.301, Xuefu Road, Jingkou District, Zhenjiang 212013, Jiangsu Province, China. Tel: +86 51188791245. Email: sun2000jun@ujs.edu.cn.

acetylcholinesterase reaches 97% at about 30℃, and its activity decreases to 80% at the temperature lower than 20℃ or higher than 40℃[11]. Thus, the level of activity influences the accuracy of measuring results. Therefore, it is of importance that the measuring data are corrected or temperature control systems are provided. Hai Yang, who developed a new type of handheld pesticide residue detector based on the analysis system of acetyl cholinesterase, applying the temperature correction technology to the instrument for the first time. However, the detector above is only applicable between 20℃ and 40℃[12]. In this study, a temperature control system, which controls the internal temperature of the detector to improve the accuracy of pesticide test results, was researched and developed as a part of a portable detector.

The process of detecting pesticide residues needs to control the temperature by enzyme inhibition. There are many complex and changeable factors affecting the temperature during practical detection. Currently, there are many methods to control temperature. It is easy to achieve the conventional PID control, but it is difficult to set the optimal parameters. Fuzzy control system can overcome the great inertia, but it cannot meet the accuracy requirements[13,14]. In view of advantages and disadvantages of traditional PID controller and fuzzy controller, fuzzy PID controller will be designed as temperature controller PID parameters by using fuzzy reasoning to adjust PID parameters online. Fu et al.[14] designed the fuzzy adaptive PID controller to control the solar drying temperature, and the simulated results showed that the controller has excellent adaptability and robustness than traditional PID controller. Zhou et al.[15] applied fuzzy PID controller in temperature control system of resistance furnace, which well proved the superiority of the fuzzy PID algorithm by experiment curves. In addition, transmission lag generally exists in temperature control systems. Du et al.[16] applied intelligent fuzzy control over the DC motor for stable and reliable stepless adjustment of the spacing of corn planter. It impairs the performance of the temperature control system, and causes serious instabilities of closed-loop systems from the sensor to the actuator. Since appropriate feedback compensation control aspects are applied in the Smith predictor control, which can eliminate the pure hysteresis loop in the denominator of the closed loop transfer function[17,18]. Pang et al.[19] adopted predictive fuzzy-PID controller which was combined using the smith predictor, the fuzzy controller and PID controller to realize the steady temperature control in center air adjusting system, and the system can not only be of high control accuracy, fast response and adaptation, but also can solve a large system lag. Qin et al.[20] researched high precision temperature control for projection lens with long time thermal response constant, against pure lag of remote transmission of cooling water circuit, the PID controller with Smith predictor was set as the inner loop sub-control algorithm, and accessed to stable control effect. Therefore, in this study the Smith predictor is added to the system to eliminate lag.

2 The system mathematical model

The shell of the pesticide residues detector is assumed to be rectangular, and its volume is considered as 40 cm×10 cm×10 cm. The two semiconductors are the refrigeration devices which can heat or cool when the direction of the current is changed. They are embedded in the left and right sidewall, respectively.

Based on the thermodynamic analysis, the process of diversification of temperature is actually the process of acquisition and loss of energy[21]. If the heat loss is ignored, the heat, which was absorbed by the air in the instrument, is equal to the heat released by the semiconductor cooler. The dynamic equation is given by Equation (1):

$$Q=\frac{2\lambda A(\theta_s-\theta_c)}{b} \tag{1}$$

where, Q is heat, J; λ is the thermal conductivity of air, W/(m·℃); A is sectional area, m^2; θ_s is sidewall temperature, ℃; θ_c is intermediate temperature, ℃; b is air thickness, m.

According to the fundamental theorem of thermodynamics, the average heat flux is defined as the ratio of heat and time within the interval, and heat is defined as the results multiplied by specific capacity, quality and the amount of temperature change[21], namely:

$$Q=\frac{CV\rho\Delta\theta}{t} \tag{2}$$

where, C is specific heat capacity of air, J/(kg·℃); V is volume, m^3; ρ is density of air, kg/m^3; $\Delta\theta$ is temperature change between the side wall and the intermediate, ℃.

Therefore, the transient heat flow equation is as presented in Equation (3):

$$Q = CV\rho\frac{d\theta}{dt} \tag{3}$$

Heat transfer between the semiconductor cooler in the side walls and the middle temperature sampling point can approximate free transfer. The dynamic equation is as expressed in Equation (4):

$$\frac{CV\rho d\theta_c}{t} = \frac{2\lambda A(\theta_s - \theta_c)}{b} \tag{4}$$

After a Laplace transform:

$$G(S) = \frac{\theta_c(s)}{\theta_s(s)} = \frac{1}{\frac{CV\rho b}{2\lambda A}s + 1} = \frac{1}{Ts + 1} \tag{5}$$

where, $\theta_s(s)$ and $\theta_c(s)$ are Laplace transformations of θ_s and θ_c, respectively; T is time constant, s. There is a delay in constant temperature control system. Therefore, the pure lag should be added to the transfer function.

$$G(s) = \frac{1}{Ts + 1}e^{-\tau s} \tag{6}$$

where, τ is pure delay time, s.

According to physical properties of air and the capacity of the instrument, the time constant was calculated ($T = 90$ s). If τ=20 s，the transfer function of the control object is shown in the following formula:

$$G(s) = \frac{1}{90s + 1}e^{-20s} \tag{7}$$

3 The system controller

The advantages of the traditional PID (Proportional-Integral-Derivative) controller include simple structure, easy implementation, and higher robustness. However, the traditional PID control is not suitable for a large inertial system, and it is difficult to match the optimal parameters. Fuzzy control not only depends on accurate mathematical models, but also overcomes the large inertia of the system. However, the fuzzy information results in decline of accuracy of the system. Besides, the dynamic performance is deteriorated. Therefore, fuzzy control and PID control are combined to form a fuzzy PID controller in this paper. In addition, there are some delays in the temperature control system, from the sensor that collects temperature inside the instrument to the semiconductor coolers which heat or cool the system. Therefore, the Smith predictor is introduced in the reverse parallel fuzzy PID controller for the purpose of temperature compensation. The lap of control variable is reflected by the Smith predictor, which causes the controller to act in advance. Thereby, some performance indicators are improved effectively.

3.1 Smith fuzzy PID controller

The structure of the Smith fuzzy PID controller is shown in Figure 1[22]. The Fuzzy controller, the PID controller and the Smith predictor controller composed the temperature controller. The Smith predictor was used to correct the lag of the system. The fuzzy PID controller was designed in the following procedure. First, e (error) and ec (error change rate) were designed as input variables of the fuzzy controller, and correction variables which are ΔK_p (correction proportional gain), ΔK_i (correction integral gain), and ΔK_d (correction derivative gain) were designed as its output variables. Second, E, EC, KP, KI, and KD are fuzzy variables which were corresponded to input / output variables of the fuzzy controller, respectively. Third, the fuzzy relation between input and output was established by self-tuning. The matrix of the correction parameter was designed by applying the fuzzy reasoning based on the membership assignment table of the fuzzy subset and the fuzzy control model of each variable. Finally, correction parameters which had been searched from the matrix above were substituted into the Formula (8) to calculate the new PID parameters. According to the above steps, PID parameters were corrected online by the fuzzy controller.

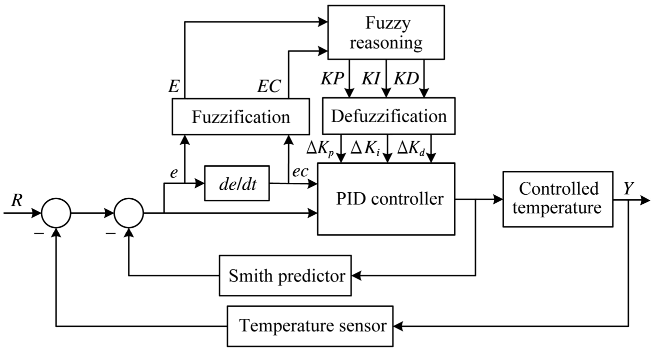

Figure 1 Structure diagram of the temperature control system based on the Smith fuzzy PID controller

$$K_p = K_p' + \Delta K_p,\ K_i = K_i' + \Delta K_i,\ K_d = K_d' + \Delta K_d \quad (8)$$

where, K_p', K_i' and K_d' are original PID parameters; ΔK_p, ΔK_i and ΔK_d are correction PID parameters; K_p, K_i and K_d are new PID parameters.

3.2 Input/output variables of fuzzy PID controller

According to the accuracy requirements of the temperature control system, the basic domain of e was from -1℃ to 1℃, and ec was from -0.5℃/s to 0.5℃/s. The fuzzy domain of E was selected from -6 to 6, and EC was selected from -3 to 3. Therefore, scale factors of K_e and K_{ec} were both 6. The fuzzy subsets of input and output variables were {NB, NM, NS, Z, PS, PM, PB}. Their respective fuzzy variables, basic domain, fuzzy sets, fuzzy domain and quantify/scale factors were shown in Table 1.

Table 1 Input / output variables of the fuzzy controller

Variables	Fuzzy variables	Basic domain	Fuzzy sets	Fuzzy domain	Quantify/ scale factors
e	E	[-1, 1]	NB,NM, NS, ZO, PS, PM, PB	[-6, 6]	6
ec	EC	[-0.5, 0.5]		[-3, 3]	6
ΔK_p	*KP*	[-12, 12]		[-6, 6]	2
ΔK_i	*KI*	[-0.75, 0.75]		[-3, 3]	0.25
ΔK_d	*KD*	[-3, 3]		[-3, 3]	1

Based on the extent of coverage of the universe, sensitivity, stability and robustness, the membership functions of E and EC were formulated as normal distribution Gaussian membership functions, which were provided with better accuracy and stability, and the membership function of E was shown in Figure 2. The triangular membership function with high precision calculation, simple form, and computational efficiency advantages was selected for ΔK_p, ΔK_i and ΔK_d, and the membership function of ΔK_p was shown in Figure 3.

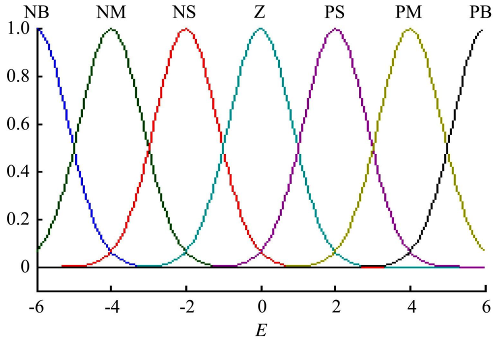

Figure 2 Membership function of E

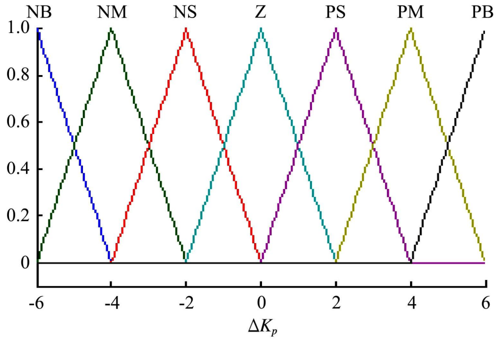

Figure 3 Membership function of ΔK_p

4 Simulation and analysis

The simulation model of the temperature control system was built in MATLAB 2009a/Simulink[23,24]. Given the same step signal with amplitude of 1, the PID controller, the fuzzy PID controller, and the Smith fuzzy PID controller were simulated, respectively. The sampling time was 10 s, the simulation of three controllers were shown in Figure 4. All parameters were set, for example, the quantization factor, the scale factor, K_p', K_i' and K_d', etc.

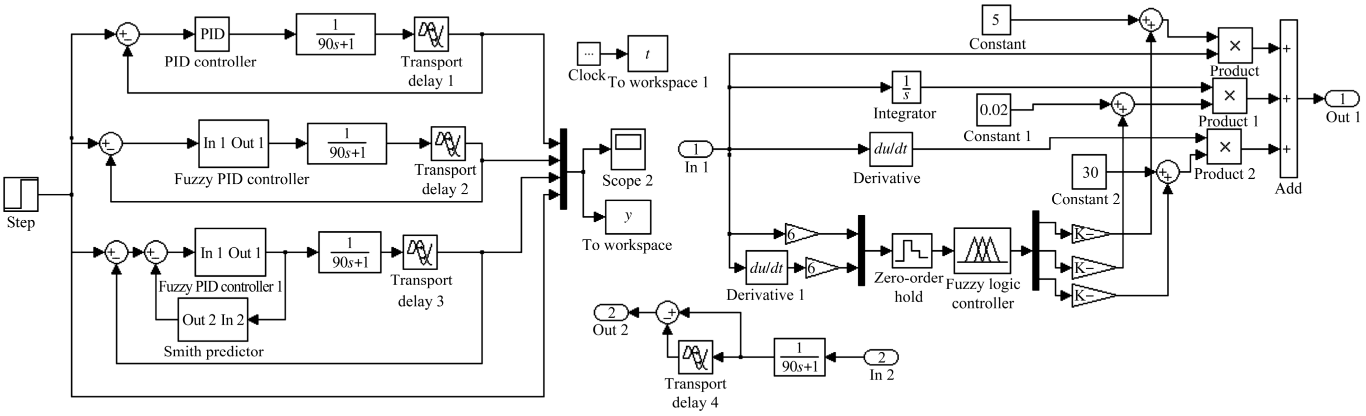

Figure 4 The simulation model of the thermostatic control system

The output characteristics of the system were shown in Figure 5 after setting the parameters. Seen from Figure 5, performance indicators of the system were as follows by the PID controller: the percent overshoot rose up to 19%; the adjustment time was about up to 250 s; and the steady-state error was almost zero. Therefore, the effect operation of controlling was not ideal entirely. Compared with the PID controller, percent overshoot of the system had been improved by the fuzzy PID controller, which decreased by 9%. However, rapidity of the system had been greatly affected, which the adjustment time increased from 250 s to 450 s. The Smith predictor was added to the fuzzy PID controller to compensate lap. Then, the system did not have error overshoot and the steady-state error. Therefore, an ideal effect operation of controlling was obtained by the Smith fuzzy controller. The conclusion is consistent with the Zhou and Zhao's research[15], the effect of Fuzzy-PID control is obviously better than conventional PID control; and the lag also be compensated as described in the literature [19]. Performance indicators of three controllers were shown in Table 2.

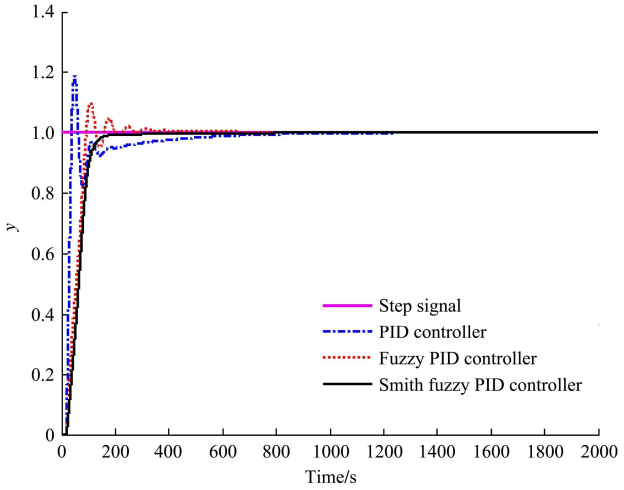

Figure 5 Output characteristics after parameters set

Table 2 Performance indexes of control algorithms

Performance indexes	PID controller	Fuzzy PID controller	Smith Fuzzy PID controller
Percent overs-hoot δ/%	19%	10%	0%
Adjustment time t_s /s	250	450	140
Steady-state error e_{ss}	0.0001	0.0001	0

4.1 Analysis of interference immunity

It is well known that the ideal control system not only needs to have good stability, speed, and accuracy, but also excellent noise immunity. There are many confounding factors of uncertainty in the process of monitoring and controlling temperature. Thus, interference immunity analysis is essential for the control system. The robustness of the temperature control system was detected by adding an interference signal with amplitude of 5 from 1 200 s to 1 230 s. Output characteristics were shown in Figure 6 after the interference signal. Seen from results of simulation, large fluctuations of output characteristic curves of the PID controller and the fuzzy PID controller appeared after the disturbance, and curves restored to the original condition after 200 s and 300 s, respectively. However, the output characteristic curve of the Smith fuzzy PID controller did not fluctuate, and recovery time is only 120 s. Thus, it has strong interference immunity. The Smith fuzzy PID controller is able to reduce the interference from uncertainty factors in the temperature control system.

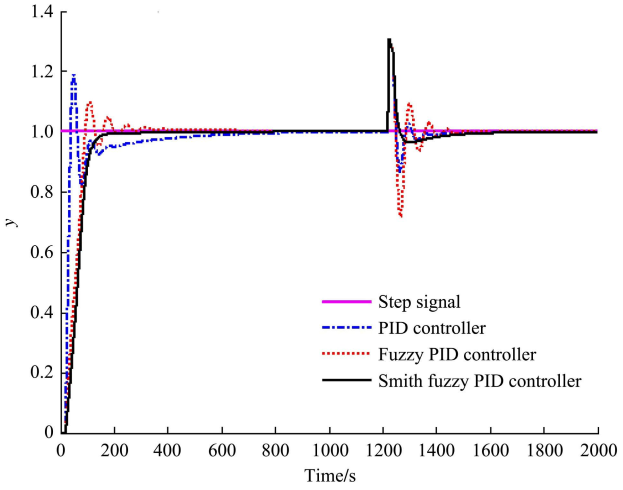

Figure 6 Output characteristics after adding interference

4.2 Analysis of robustness

Actually, T (time constant) and τ (lag time) in Equation (8) are not unchanged. Thus it is of necessity for the temperature control system to analyze the robustness. For the purpose of comparing the robustness of controllers, only T and τ were changed. If T was 120 s, and τ was 30 s, the output characteristics of the system were shown in Figure 7. Seen from Figure 7, percent overshoots and adjustment times of the PID controller and the fuzzy PID controller significantly increased after changing T and τ, and there was a tendency of shock. However, percent overshoots and adjustment times of the system which was added to the Smith predictor controller contributed to a better indicator. Therefore, the Smith fuzzy PID controller possesses strong robustness. Performance indicators of three controllers are shown in Table 3.

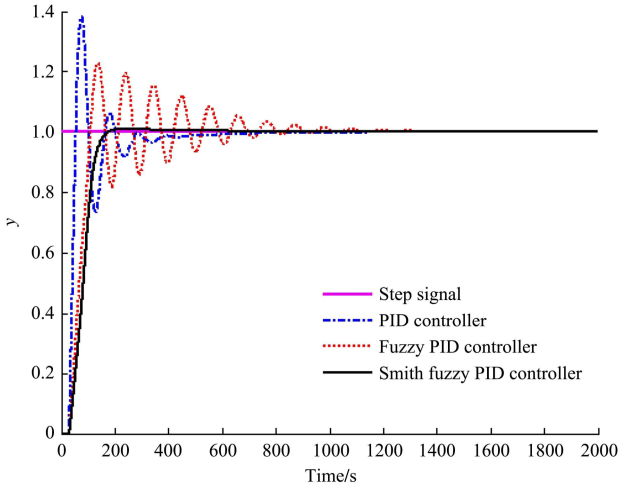

Figure 7 Output characteristics after parameters changed

Table 3 Performance indexes of control algorithms after changing parameters

Controller	Performance indexes		
	Percent overs-hoot δ/%	Adjustment time t_s/s	Steady-state error e_{ss}
PID	38	450	0.0001
Fuzzy PID	23	880	0.00025
Smith Fuzzy PID	1	150	0

5 Conclusions

1) Based on thermodynamics, the mathematical model of the controlled object was established by the mode of heat transfer. On the basis of the mathematical model, the simulation model of the temperature control system was built in MATLAB.

2) A Smith fuzzy PID controller was studied by the Smith predictor combined with the fuzzy PID controller. The PID controller, the fuzzy PID controller, and the Smith fuzzy PID controller were simulated under the same conditions. From the simulation results, performance indicators of the Smith fuzzy PID controller are superior to the PID controller and the fuzzy PID controller. Therefore, the Smith fuzzy PID controller can not only improve the lag of the system effectively, but also enhance the robustness and immunity of the system.

3) The temperature control system based on the Smith fuzzy PID controller can precisely control the temperature inside the instrument. Therefore it is able to provide the best temperature for the enzymatic detection to ensure the accuracy of the results.

Acknowledgement

This work is supported by the National Natural Science Fund Project (31471413), Project A funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and Natural Science Fund Project of Jiangsu Province (BK20141165), China Postdoctoral Science Foundation funded project (2014M561594), Jiangsu Planned Projects for Postdoctoral Research Funds (1401175C).

[References]

[1] Duford D A, Xi Y Q, Salin E D. Enzyme inhibition-based determination of pesticide residues in vegetable and soil in centrifugal microfluidic devices. Analytical Chemistry, 2013; 85(16): 7834–7841.

[2] Guo X S, Zhang X Y, Cai Q, Shen T, Zhu S M. Developing a novel sensitive visual screening card for rapid detection of pesticide residues in food. Food Control, 2013; 30(1): 15–23.

[3] Mishra RK, Deshpande K, Bhand S. A high-throughput enzyme assay for organophosphate residues in milk. Sensors, 2010; 10(12): 11274–11286.

[4] Campanella L, Bonanni A, Martini E, Todini N, Tomassetti M. Determination of triazine pesticides using a new enzyme inhibition tyrosinase OPEE operating in chloroform. Sensors and Actuators B: Chemical, 2005; 111-112(11): 505–514.

[5] Qiu C K, Liu X Y, Ren H Y, Jiang F. Study on detection of organophosphorus pesticide residue in vegetables by enzyme inhibition method. Food and Machinery, 2010; 26(2): 40–42. (in Chinese with English abstract)

[6] Luan Y X, H P, Lu A X, Pan L G. Detection of contamination in fruits and vegetables with a portable rapid detector. Transactions of the CSAM, 2009; 40 (Supp.): 146–149. (in Chinese with English abstract)

[7] Wang X Y, Wang X Y, Sun X, Sun D X. Optimization of determination for pesticide residues in vegetables. Transactions of the CSAM, 2008; 39(4): 97–100. (in Chinese with English abstract)

[8] Zheng Y H , Hua T C, Sun D W, Xiao J J, Xu F, Wang F F. Detection of dichlorvos residue by flow injection calorimetric biosensor based on immobilized chicken liver esterase. Journal of Food Engineering, 2006; 74(1): 24–29.

[9] Llopis X, Pumera M, Alegret S, Merkoci A. Lab-on-a-chip

for ultrasensitive detection of carbofuran by enzymatic inhibition with replacement of enzyme using magnetic beads. Lab on a Chip, 2009; 9(2): 213–218.

[10] Valdes-Ramirez G, Fournier D, Ramirez-Silva M T, Marty J L. Sensitive amperometric biosensor for dichlorovos quantification: Application to detection of residues on apple skin. Talanta, 2008; 74(4): 741–746.

[11] Qiu Z J, Lu J Ff, He Y. Rapid detection system development and influence factor analysis for pesticide residues in agricultural products by enzyme inhibition method. Transactions of the CSAE, 2007; 23(9): 229–233. (in Chinese with English abstract)

[12] Yang H, Jin W, Wang L L, Su M W, Zheng Y B, Lu X H. A New hand-held pesticide residue monitor instrument with temperature correction function. Chinese Journal of Analytical Chemistry, 2005; 33(7): 1041–1044. (in Chinese with English abstract)

[13] Li L, Zhu L, Jiang Q, Zhang M. Simulation of temperature control algorithm in micro flow-through PCR system. Transactions of the CSAM, 2012; 43(Supp.): 295–299. (in Chinese with English abstract)

[14] Fu L S, Sun X J, Wu X H, Piao Z L, Hai P. Application of fuzzy adaptive PID controller in solar drying temperature control. Transactions of the CSAE, 2006; 22(7): 217–219. (in Chinese with English abstract)

[15] Zhou L Y, Zhao G S. Application of fuzzy-PID control algorithm in uniform velocity temperature control system of resistance furnace. Chinese Journal of Scientific Instrument, 2008; 29(2): 405–409. (in Chinese with English abstract)

[16] Du R C, Gong B C, Liu N N, Wang C C, Yang Z D, Ma M J. Design and experiment on intelligent fuzzy monitoring system for corn planters. Int J Agric & Biol Eng, 2013; 6(3): 11–18.

[17] Wang B Z, Song D F, Liu W F. Improved PID control based on Smith predictive compensation and RBF neural network. Modern Electronics Technique, 2011; 34(5): 153–157.

[18] Lin D L, Shen E D, Zhang K Y, Yu L W. Greenhouse control using geothermal water heating system. Transactions of the CSAM, 2009; 40(2): 151–154, 219. (in Chinese with English abstract)

[19] Pang L P, Wang J, Liu W K. Application of predictive fuzzy-PID in center air adjusting control system. Journal of Beijing University of Aeronautics and Astronautics, 2004; 30(8): 757–761. (in Chinese with English abstract)

[20] Qin S, Gong Y, Yuan W Q, Yang H J. High precision temperature control for projection lens with long time thermal response constant. Optics and Precision Engineering, 2013; 21(1): 108–114. (in Chinese with English abstract)

[21] Chen L. Medical thermostat temperature control system. Beijing: Beijing Jiaotong University, 2007. (in Chinese with English abstract)

[22] Xiao J M, Zhu H M, Jiao L Y, Zhang R. Based on Fuzzy -PID self-tuning temperature control system of the furnace. 2011 International Conference on Electric Information and Control Engineering, 2011; 1203–1206.

[23] Shan C X, Chen W J, Peng J. Design and simulation of temperature control system of heating exchanging station based on fuzzy PID control. Instrument Technique and Sensor, 2011; 9: 79–82. (in Chinese with English abstract)

[24] Zhang Y H. Application of Fuzzy PID-Smith cascade control in heating furnace temperature control system. Control and Instruments in Chemical Industry, 2012; 8: 979–981. (in Chinese with English abstract)