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Research on Fuzzy Fractional Order PID Control of Liquid Temperature in Displacement Digester

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ABSTRACT

In order to reveal the delay and nonlinear characteristics of cooking liquid in the heating process, PID heating control would produce overshoot. In this paper, the traditional cascade PID control was designed to control the temperature of cooking pot. The analysis of the experimental results showed that the PID control method would cause a large overshoot, which was easy to cause the temperature control out of control phenomenon, and it was easy to cause a large temperature difference between the top and bottom parts of the cooking liquid. Therefore, by combining fractional order PID control with fuzzy logic control, a fuzzy fractional order PID cascade decoupling control strategy was proposed. Finally, compared with traditional cascade PID control, this method could realize online adjustment and optimization of fractional PID controller parameters, and could effectively improve the dynamic characteristics of liquid temperature control system, which proved the feasibility of this control strategy.

Keywords: *Displacement digester, liquid temperature, Fuzzy fractional order PID controller*

1. Introduction

As the main production technology of chemical pulp, batch cooking includes traditional batch cooking and displacement cooking. The production of chemical pulp is mainly based on wood/bamboo raw materials. The traditional batch cooking technology has the problems of high energy consumption, large pollution, and low pulp yield. Displacement Digester System (DDS) is a true energy-saving and environment-friendly pulping technology. By adding warm and hot black liquor tanks, hot

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white liquor tanks and other tanks and public auxiliary pipelines, the utilization of heat in the cooking black liquor and the recovery of chemicals are realized. It is the main direction for the future development of cleaner production in pulping technology.

As an important stage of chemical pulping, the quality of raw pulp obtained directly affects the subsequent processes such as washing and bleaching. The DDS cooking pot is a large airtight container. During the cooking process, the temperature in the cooking pot needs to reach the optimal cooking temperature of the material. If the cooking temperature is too high, it is easy to overcook and affect the pulp quality. If the cooking temperature is too low, it will increase the cooking time and affect production efficiency. In order to obtain higher pulp quality, improve production efficiency, and further utilize the advantages of displacement cooking technology, many scholars have carried out research on DDS displacement cooking system from different aspects. To improve pulp quality, reduce energy consumption and material waste, Sheoran et al.[1] used bromine-82 as a tracer to measure the distribution of chemical components in the cooking pot. At the same time, based on the analysis of the liquid phase flow kinetics, the residence distribution of the liquid phase in the pulping and cooking process was analyzed, and the optimal cooking process conditions were found. Intelligent optimization algorithms[2-5] have used to select the primary and secondary variables in the cooking liquor that affect pulp quality, and studied the Kappa number soft sensor. Hongliang[6] made a detailed analysis of the problems of using soft-sensing technology to measure the Kappa value of pulp from the aspects of soft-sensing modeling methods, selection of model variables, and online correction of measurement models. Aiming at the difficulties of online measurement of pulp Kappa value and the large hysteresis caused by traditional measurement methods, Wei et al[7] had made related research on the application of spectroscopic technology and hybrid algorithm to Kappa value soft measurement, which overcame the difficulty of measurement and improved the prediction.

The above research started from various aspects to find the best cooking end point to improve the pulp quality of the cooking process, but did not consider the effect of cooking temperature on the production process. The site environment is complex and changeable, and there are many factors that affect the temperature rise of the chemical liquid, such as the fluctuation of the chemical liquid flow rate in the top and lower return pipes, the fluctuation of the medium-pressure steam pressure, the pressure in the cooking pot, and the change in the external ambient temperature. In order to prevent the phenomenon of raw pulp when the cooking temperature is low, or the phenomenon of rotten pulp when the cooking temperature is too high, it is required that the temperature difference between the top and lower parts of the cooking pot should not exceed 5℃. The ultimate goal of temperature control is to ensure that the pulp temperature in each part of the cooking pot is as consistent as possible on the premise of ensuring the quality of the pulp, to reduce the Kappa value in the pulp as much as possible, and to improve the pulp yield. The traditional PID control is easy to cause large overshoot in the process of chemical liquid control, and it is difficult to meet the higher process requirements.

The fractional PID controller is an extension of traditional PID controller. By adding two adjustable differential order λ and integral order μ, the design can be more flexible, and it can show better superiority to the control system with nonlinearity and time delay. In addition, its strong robustness attracts the attention of scholars.[8,9] The chemical liquid temperature control system is complex and the controlled object has non-linear characteristics. This applies to the fractional order PID controller to the control system to improve its stability and increase its parameter setting workload.[10,11] Fuzzy control does not need to rely on an accurate mathematical model of the controlled object, and it has good self-adaptability to the control system with nonlinearity and large delay, and shows good robustness.[12]

According to the characteristics of the chemical liquid temperature control system, the fractional PID controller was used as the main controller of the chemical liquid temperature cascade control. Combined with the fuzzy controller, a fuzzy fractional PID cascade control strategy was proposed. This strategy could use fuzzy logic to adjust the parameters of the fractional PID controller in real time to improve the stability of the liquid temperature control process.

2. Process Description and Control Methods

2.1 DDS process

This experiment was performed in a paper-making mill in Hubei. The DDS process in the mill is shown in Fig. 1. By adding warm black liquor tank, hot white liquor tank, cold white liquor tank and other public auxiliary equipment, this system can realize the heat energy recovery of black liquor while preparing the slurry, reducing the cooking process. The entire cooking cycle can be divided into six stages: Liquor Charge, Initial Cooking, Middle Cooking, Final Cooking, Recovery Cooking, and Discharge Cooking. When the system enters the pot filling stage, the material conveyor belt starts to run. Put the wood chips and cooking liquor into the cooking digester. After the pot-filling phase is over, the system enters the primary

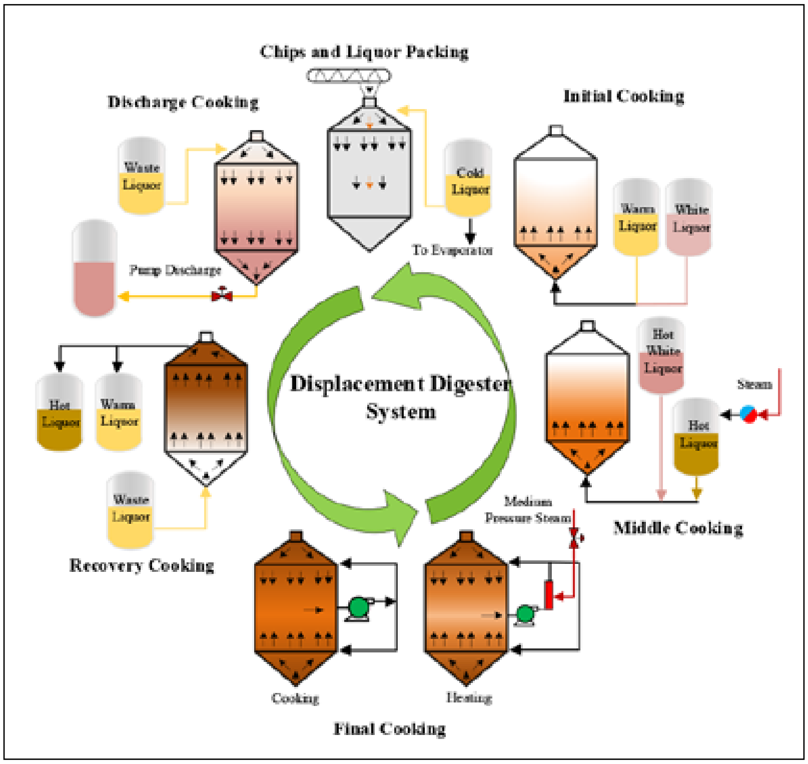


Fig. 1. Process flow chart of DDS.

cooking stage. Warm black liquor and cold white liquor are pumped from the bottom of the cooking digester into the cooking digester, and the cold black liquor is replaced at the same time. In the intermediate cooking stage, hot black liquor and hot white liquor are mixed and pumped into the cooking pot to replace the warm black liquor. When the filling amount of hot black liquor reaches the set value, the intermediate cooking stage ends, the H factor counting subroutine starts to run, and the liquid medicine in the cooking pot enters the heating cooking process. After the H factor reaches the set value, to prevent the high-temperature pulp from staying in the cooking pot for too long, which will reduce the quality of the pulp, the system should directly enter the replacement stage. After the replacement is completed, the cooking pot is in a state of low temperature and normal pressure, and it can enter the pot laying stage. After the slurry is sent to the spray pot, a cooking cycle is completed.

As described in the DDS process, the heating of the cooking chemical liquid was carried out in the temperature increase/insulation stage. At this time, the temperature of the chemical liquid was heated to the optimal cooking temperature, and this stage would further remove the residual lignin. After the hot black liquor was filled, the temperature of the cooking liquid reached about 150℃. In order to make the temperature of the cooking pot reach the optimal cooking temperature, the medium-pressure steam indirect heating method was used to achieve the heating of the cooking liquid. The process flow of final cooking is shown in Fig. 2. After the circulation pump extracted the middle liquid of the cooking pot and heated it to the top through the steam heat exchanger, it flowed into the top and the bottom of the cooking pot from the top and bottom parts of the return pipeline respectively. Finally, the low-temperature chemical liquid was replaced by the high-temperature chemical liquid so that the temperature in the cooking pot reached the set cooking temperature. The return flow of the top and bottom pipelines was regulated and controlled by the flow regulation valve of the top pipeline and the flow regulation valve of the bottom pipeline respectively. The flow regulation valve used in the experiment is shown in Fig. 3. Considering the airtightness and safety of the cooking pot, the temperature of the liquid medicine in the cooking pot could not be measured directly. The temperature transmitter was installed at the outlet of the top and bottom headers and the entrance of the middle header. The measured liquid temperature was approximated as the top, bottom and middle liquid temperature of the cooking pot. The temperature transmitter used in the experiment is shown in Fig. 4.

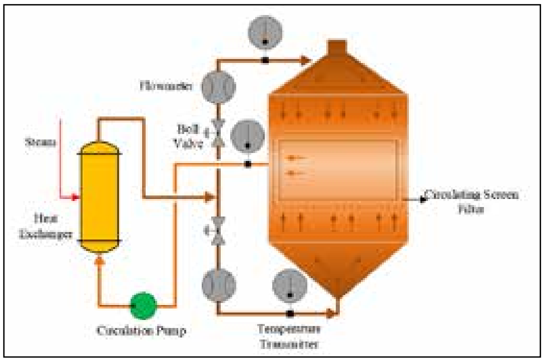


Fig. 2. The process flow of final cooking.

Fig. 3. The flow regulation valve.

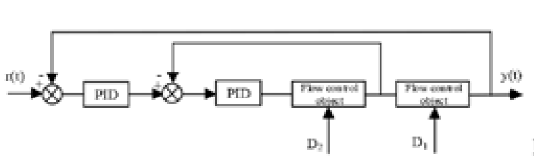
Fig. 4. The temperature transmitter.

2.2 Control method for the experimental device

According to the mechanism of the temperature increase of the chemical liquid, the temperature control of the top chemical liquid was taken as an example for analysis, and an appropriate temperature control method of the cooking pot was selected. The temperature of cooking liquor in the cooking pot was the ultimate control target in the heating stage. If a single closed loop control of liquid temperature was formed with the boiler temperature as the controlled object and the flow control valve as the executive organ, the control mode was easy to cause the movement range of the flow control valve to be too large. The smoothness of liquid flow could not be guaranteed and the temperature control effect was often non-ideal. At the same time, considered many interfering factors in this process, a secondary control loop consisting of a flow transmitter and a control valve was installed in the top pipeline to include liquid flow interference in this loop. The temperature of the cooking liquid was the controlled object of the main control loop. The pressure fluctuation of the cooking pot was taken as the primary disturbance to form the cascade control mode with the liquid flow regulation as the secondary control loop and the liquid temperature control as the main control loop. The temperature control structure of liquid is shown in Fig. 5.

Medium pressure steam adopted temperature difference control method for the heating process of chemical liquid. When the temperature TH of the cooking pot was higher than the set value of 2℃, the medium-pressure steam valve would close and stop heating, and the circulating pump P-009 would continue to operate to homogenize the temperature of the liquid medicine in the cooking pot, so as to ensure the uniformity of the temperature of all parts of the liquid medicine in the cooking pot. If the H factor reached the target value, the heating/insulation stage would be over. In the cooking process, the cooking pot was always under high temperature and high pressure. To ensure the normal pressure in the cooking pot and avoid dangerous accidents, the pressure in the cooking pot was interlocked with the pressure regulating valve PIC-003a and the safety valve, as shown in Fig. 6.

The DDS system used 400 PLC as the controller and WinCC as the upper computer. The data collected from the field would be transmitted to PLC, and the whole system could be controlled orderly and run safely according to the formulated process sequence and logic program. The data to be monitored was transferred to the WinCC upper com-



D1: One disturbance ; D2: Secondary disturbance

Fig. 5. The temperature control structure of liquid.

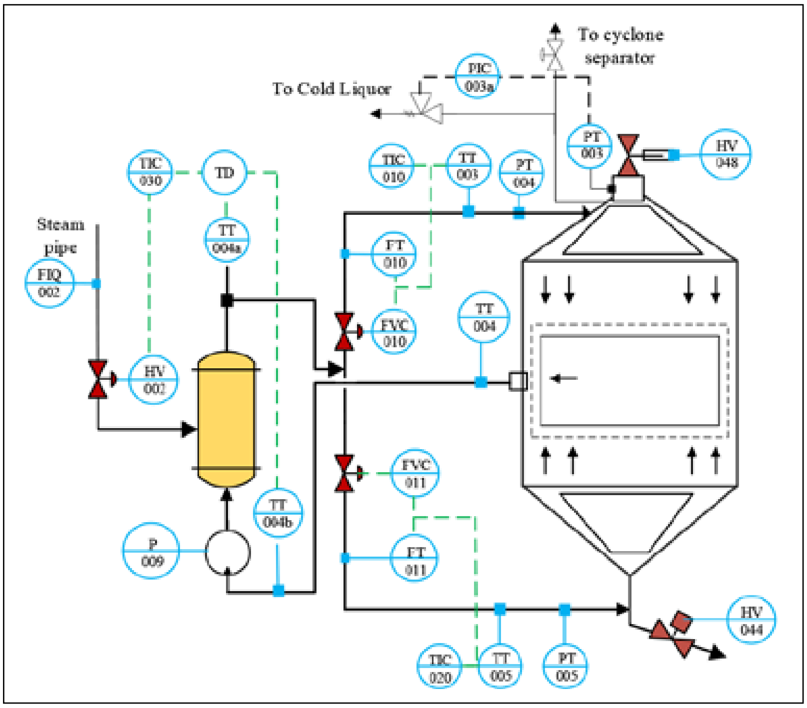


Fig. 6. Cascade Control Method of Liquor Heating.

puter for monitoring. In order to realize the advanced algorithm to control the liquid in the cooking pot, OPC (OLE for Process Control) technology was adopted in this scheme. OPC configuration was carried out in WinCC, and data transmission between WinCC and Matlab was realized through OPC toolbox in Matlab. The data of the control valve in the top computer was transmitted to PLC, and the action of the actuator was controlled after processing by the signal module. Communication schedule of Matlab and WinCC is shown in Fig. 7.

2.3 Frictional order PID controller

The fractional order PID control system can be represented by the structure in Fig. 8. The input signal of the control system is r(t); the output signal of the control system is y(t); the error signal of the system is $e(t)=r(t)-y(t)$; the fractional order controller is $G_{fc}(s)$; the controlled object is $G_p(s)$.

According to Fig. 8, the output of fractional PID controller can be expressed as follows:

$$u(t)=k_i e(t)+k_{i0} D_t^{-\lambda} e(t)+k_{d0} D_t^{\mu} e(t) \qquad [1]$$

The transfer function expression of fractional-order PID controller is:

$$G_{fc}(s)=\frac{U(S)}{E(S)}=k_p+\frac{k_i}{s^{\lambda}}+k_d s^{\mu},(0<\lambda,\mu<2) \qquad [2]$$

The structure of fractional PID controller is shown in Fig. 8 in the dotted line. The proportional, integral and differential coefficients of the controller are *kp*, *ki*, *kd* respectively. The integral order and differential order of the controller are λ and μ respectively. In order to ensure better dynamic performance and stability of the controller, the value range of the micro product order is $0<\lambda, \mu<2$. Compared with the classical PID control-

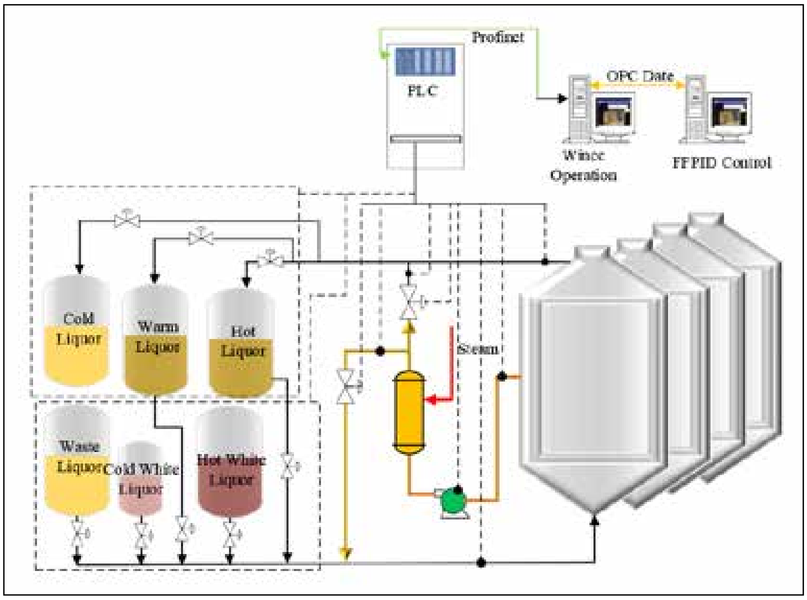


Fig. 7. Communication schedule of Matlab and WinCC.

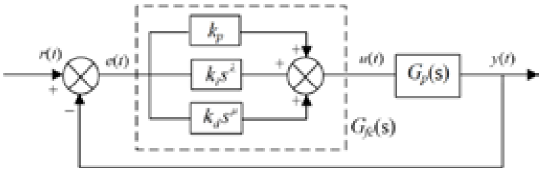
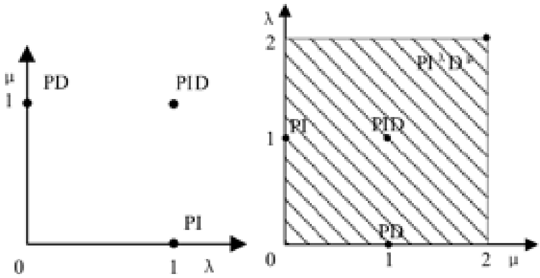


Fig. 8. Construction diagram of Fractional order PID control system.

ler, the differential and integral order adjustment range of fractional order PID controller is expanded from point to surface, making its adjustment more flexible, as shown in Fig. 9. If λ=1, μ=0 , it is PI controller; If λ=0, μ=1, it is PD controller. If λ=μ=1, it became the classic PID controller. Therefore, the traditional PID controller is a special form of fractional order PID controller, fractional order PID controller is an extension of the traditional PID controller. According to the mathematical model of the controlled object and the design requirements of the control system, different forms of controllers can be designed, such as PI^{λ} controller, $I^{\lambda}D^{\mu}$controller and $PI^{\lambda}D^{\mu}$controller. It can be applied not only to integer order control system, but also to fractional order control system.



(a) The traditional PID Controller (b) The fractional order PID Controller

Fig. 9. Comparison of the value range of the traditional PID and fractional order PID.

Discrete method is the key to digital realization of fractional PID controller, which can be divided into direct discrete method and indirect discrete method.[13] The direct discrete method is to transform fractional calculus operator into integer order system by Z transformation, and then to carry out further numerical simulation for integer order system. The accuracy of discrete approximation is related to the sampling time T. Due to the number of direct discrete methods, it is necessary to know the original form of generating function when the

Z domain is converted to the S domain, which greatly increases the uncertainty and difficulty of the work.[14,15] Indirect discretization method is to approximate the irrational function of calculus operator into integer order transfer function, among which the conventional Oustaloup approximation method is the most commonly used, but it's fitting effect is poor at both ends of the frequency band to be fitted.[16] Therefore, the modified Oustaloup indirect realization method is adopted to improve the fitting accuracy of the two segments of the selected frequency band by introducing b and d coefficients, and the fractional PID controller designed has good robustness.

In the approximate frequency band $[w_b, w_h]$ fractional calculus operator can be represented by fractional order model $K(s)$[17]:

$$K(s)=\left(\frac{1+\frac{s}{dw_b/b}}{1+\frac{s}{bw_h/d}}\right)^{\alpha}=\left(\frac{bs}{dw_b}\right)^{\alpha}\left(1+\frac{-ds^2+d}{ds^2+bsw_h}\right)^{\alpha} \quad [3]$$

In Eq. $3, 0<\alpha<1, s=jw, b>0, d>0$

After Taylor expansion of $\left(1+\frac{-ds^2+d}{ds^2+bsw_h}\right)$ in Eq. 3, $K(s)$ is expressed as:

$$K(s)=\left(\frac{bs}{dw_b}\right)^{\alpha}\left(1+\alpha p(s)+\frac{\alpha(\alpha+1)}{2}p^2(s)+\cdots\right) \quad [4]$$

$$p(s)=\frac{-ds^2+d}{ds^s+bsw_h} \quad [5]$$

Based on Eqs. 3–4, s^α is transferred to simplify, and the following equation can be obtained:

$$s^{\alpha}=\left(\frac{dw_b}{b}\right)^{\alpha}\left(\frac{1}{1+\alpha p(s)+\frac{\alpha(\alpha-1)}{2}p^2(s)+\cdots}\right)\left(\frac{1+\frac{s}{dw_b/b}}{1+\frac{s}{bw_h/d}}\right) \quad [6]$$

Taylor expansion is approximated to the first order, and Eq. 5 is substituted into the simplification to obtain:

$$s^{\alpha}\approx\left(\frac{dw_b}{b}\right)^{\alpha}\left(\frac{ds^2+bw_hs}{d(1-\alpha)s^2+bw_hs+d\alpha}\right)\left(\frac{1+\frac{s}{dw_b/b}}{1+\frac{s}{bw_h/d}}\right) \quad [7]$$

Where $K(s)$ is represented by a rational transfer function:

$$K(s)=\lim_{N\to\infty}K_N(s)=\lim_{N\to\infty}\prod_{k=-N}^{N}\frac{1+s/w_k'}{1+s/w_k} \quad [8]$$

In Eq. 8, zero and pole w_k', w_k are :

$$\begin{cases} w_k'=\left(\frac{b}{d}\right)^{\frac{2k-\alpha}{2N+1}} w_h^{\frac{N+k+\frac{1-\alpha}{2}}{2N+1}} w_b^{\frac{N-k+\frac{1+\alpha}{2}}{2N+1}} \\ w_k=\left(\frac{b}{d}\right)^{\frac{2k+\alpha}{2N+1}} w_h^{\frac{N+k+\frac{1+\alpha}{2}}{2N+1}} w_b^{\frac{N-k+\frac{1-\alpha}{2}}{2N+1}} \end{cases} \quad [9]$$

Therefore, the approximate expression of fractional calculus operator is obtained by further sorting out[18]:

$$G_F(s)=(w_bw_h)^{\alpha}\left(\frac{ds^2+bw_hs}{d(1-\alpha)s^2+bw_hs+d\alpha}\right)\prod_{k=-N}^{N}\frac{1+s/w_k'}{1+s/w_k} \quad [10]$$

The approximate order range of s^α is $0<\alpha<1$. When the approximate order is $\alpha \geq 1$, it can be expressed as: $s^{n}=s^{n}s^{\alpha}$, N is an integer.

According to the analysis of Eq. 10, the approximate integer order transfer function has order 2N+3. Taonian[19] has verified that with the continuous increase of N value, the approximation effect gets better and better. However, when N is large enough and then increases, the approximation accuracy and order no longer change in proportion. Therefore, based on the comprehensive approximation accuracy, the approximate order N=4, parameter B=10, and d=9 were taken in combination with the experimental test and practical experience.[20] As shown in Fig. 11, within the range of the selected frequency band [0.001,1000], approximate order N=4, B=10, d=9 is taken to approximate the differential order by using the traditional Oustaloup method and the improved method.[21–23] Theoretically, the amplitude-frequency characteristic curve of $s^{0.5}$ is $L(w)$, and the phase-frequency characteristic is $\varphi(w)=\pi/2$. Within the set frequency band range, the traditional Oustaloup method has a large fitting error in frequency band 10^{-3} and 10^{3}, while the improved Oustaloup method has a much better approximate effect in the whole set frequency band range than the traditional Oustaloup method. In this paper, the fractional-order $PI^{\lambda}D^{\mu}$ controller was designed by using the improved approximation method.

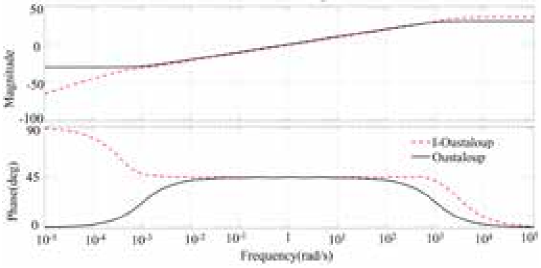


Fig. 10. Bode Diagram of Oustaloup and I-Oustaloup.

3. Results and Discussion

3.1 Results

The traditional PID cascade control method was used to control the temperature rise of the cooking liquid in the cooking pot. The auxiliary loop controller controlled the flow control valve. In order to improve the sensitivity of the control valve to flow change, the auxiliary controller was set as a pure proportional controller, and the proportion parameter was chosen 5. According to experience, PID controller parameters were set as: kp=12, ki=0.15, kd=300. When the temperature of the liquid reached 150℃ in the intermediate cooking stage, the medium pressure steam valve opened and the temperature of the liquid in the cooking pot was controlled. The final cooking temperature would be maintained at about 165℃. The internal parameters of the cooking pot during the heating test were shown in Table 1.

When the cooking system entered the intermediate cooking stage, the hot black liquor was pumped from the bottom of the cooking pot into the cooking pot, and the warm black liquor was returned from the top of the cooking pot through the collecting pipe to the warm black liquor tank. When the temperature of liquid medicine in the cooking pot reached 150℃, the system entered the heating stage. Since the top flow control loop of cooking liquid was the same as the bottom flow control loop, in order to analyze the temperature rise curve

Table 1. Cooking pot parameters during experiment

Situation	Parameter
Medium steam pressure	0.5MPa
End of medium cooking temperature	150℃
Pressure on the cooking pot as the temperature rises	0.65MPa
Internal pressure limit of cooking pot	0.9MPa
Set the cooking temperature	165℃

more intuitively and clearly, the top temperature data collected by Matlab was used to draw the temperature rise curve, as shown in Fig. 11. It can be analyzed from the figure that the temperature rising speed of the liquid medicine was fast, the curve was steep, and the highest temperature reached 170℃. The temperature regulation process was fast, and there was a large overshoot.

3.2 Discussion

The cooking pot has a special internal structure, and the reaction during the whole demineralization stage is complex. It is difficult to express the temperature rise process of liquid medicine with accurate mathematical model, so the temperature object of liquid medicine has nonlinear characteristics. At the same time, the cooking pot is a large sealed container. In the process of temperature rise, the high temperature liquid reflux is used to increase the temperature of the liquid. The temperature rise process has time-delay characteristics and the liquid circulation time is long. As can be seen from the temperature rise curve of cooking liquid, adopting PID control mode has a large overshoot, which is easy to cause the phenomenon of temperature control out of control, and also easy to cause a large temperature difference between the top and lower parts of cooking liquid. For obtaining higher quality pulp, liquid temperature should not be too fast. Although PID cascade control can meet the basic control of liquid temperature, in the face of complex site environment and liquid temperature objects with nonlinear, time-delay characteristics, it is often not ideal in terms of energy saving and pulp quality control.[24)]

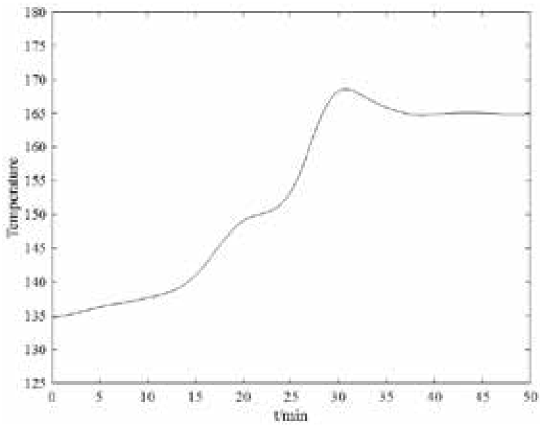


Fig. 11. Cascade PID control liquid temperature rise curve.

3.2.1 Influence of parameters of fractional controller on system performance

The other two parameters of the fractional order PID controller λ and μ are the order of integral and differential, respectively. From the mathematical point of view, its value represents the strength of the differential and integral of the error. Similar to kd and ki value, integral order and differential order affect the regulation time, stability and error accuracy of fractional order PID control system.

Taking the liquid temperature control system as an example, the mathematical model of each part of the temperature control circuit of the top channel is taken as follows[25)]: the transfer function of liquid temperature is $Gp(s)=\frac{0.00001855}{s^2+0.035s+0.00015}e^{-7s}$, the top flow object is $G_{11}(s)=\frac{2}{s+0.25}$, the following is the analysis of the fractional PID controller calculus order on the performance of the control system.

When the integral order λ was between 0.8 and 1.4, the change curve of the control system was shown in Fig. 12. When λ was equal to 0.8, the system had the characteristics of faster reaction speed and better stability, but its steady-state error was very large. The integral effect of the control system would be enhanced with the increase of the value, and the steady-state error of the system would disappear. When λ gradually risen, overshoot occurs and its steady−state performance decreased. When λ=1.4, the overshoot of the sys−tem increased, even oscillation occurred, and the system was difficult to reach a stable state. There−fore, the selection of integral order in the range of 1.0~1.2 can make the liquid temperature control system achieve ideal control effect.

By selecting different μ values, their effects on the control system can be clearly reflected, and an appropriate value range can be determined. The change curve is shown in Fig. 13.

It can be seen from the figure that, in order to maintain the stability of the system, the differential coefficient should be between 0.8 and 1.2, because with the gradual increase of the differential coeffi−cient, the curve fluctuation will be larger, and the time to reach the stable state will be longer.

3.2.2 Design of Fuzzy Fractional Order PID Controller

Fuzzy Logic Controller is a process that simulates human reasoning and decision−making. It converts accurate digital signal into a kind of Fuzzy quan−tity through a certain membership function. Sec−ondly, according to the rules designed in advance with expert knowledge in the knowledge base, the decision is made according to some reasoning way. Finally, the fuzzy quantity is clearly converted into precise quantity output. Based on fuzzy control theory, the fuzzy controller according to the num−ber of input variables can be divided into one−di−mensional, two−dimensional and three−dimen−sional controller, with the increase of input vari−ables, the design of the fuzzy rules are more com−plicated, the error calculation quantity is big, and

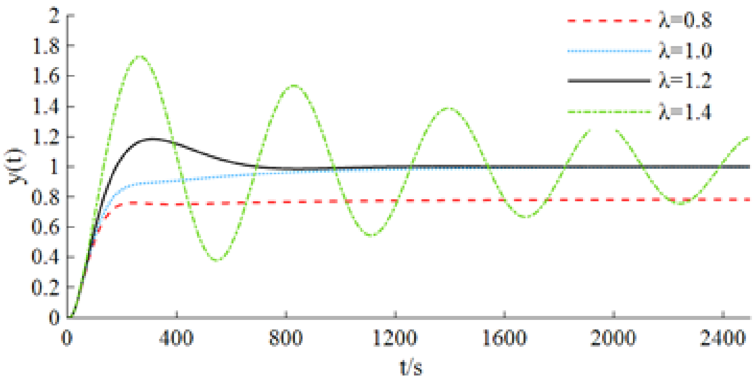


Fig. 12. Step response of λ with different values.

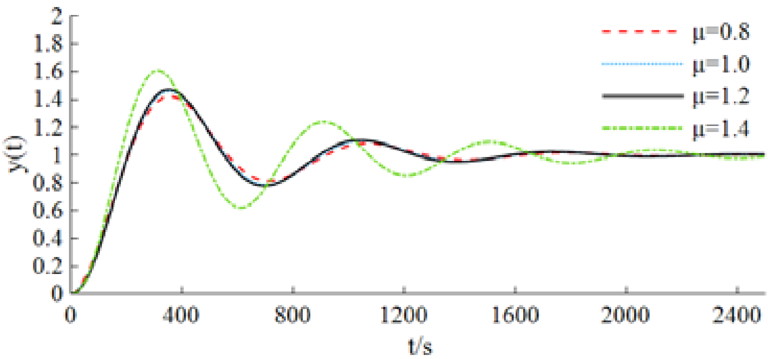


Fig. 13. Step responses of μ with different values.

less input variable is unable to reflect the change of system in detail, the advantages of the fuzzy controller can't perfect embodiment. In order to better reflect the changing trend of system response and reduce unnecessary variable input, a fuzzy fractional PID controller with two inputs and three outputs was designed. The structure principle of the fuzzy fractional PID control system is shown in Fig. 14.

System error signal $e(t)=r(t)-y(t)$ and the error change rate $ec(t)=e(t)-e(t-1)$ as input variable of fuzzy controller, the expert knowledge and practical experience in the form of language description form the knowledge base, through fuzzy reasoning and motivation to achieve accurate variable output, it to the fractional order PID controller and the real-time adjustment of fractional order PID three parameters kp, ki, kd. Combined with the advantages of the two controllers, the control strategy can solve the problem that the control precision of the fuzzy controller is not high and the parameters of the fractional PID controller cannot be fixed, and the parameters of the fractional PID controller can be adjusted adaptively.

$$kp = kp_0 + \Delta kp \qquad [11]$$

$$ki = ki_0 + \Delta ki \qquad [12]$$

$$kd = kd_0 + \Delta kd \qquad [13]$$

In Eqs. 11–13, kp_0, ki_0, kd_0 are the initial value, $\Delta kp=f_1(e, ec)$, $\Delta ki=f_2(e, ec)$, $\Delta kd=f_3(e, ec)$,

According to the structure of the two-dimensional fuzzy controller, the temperature change e and the temperature change rate ec detected by the temperature transmitter in the cooking pot are taken as the input variables of the fuzzy controller. The e domain is converted to [−6,6], and the temperature change rate ec domain is converted to [−3,3]. Δkp, Δki, Δkd are output variables of the fuzzy controller. Δkp and Δkd are converted to [−6,6], and Δki are converted to [−1,1]. In order to express the change rule of the system more accurately, the fuzzy subset of input and output variables was described by NB, NM, NS, Z, PS, PM and PB.

In fuzzy control, membership function has a great influence on the control performance. The selection rules are as follows: the membership function with low resolution is used in control system with large error range to improve the stability of the system. In order to improve the sensitivity of the system, the fuzzy set of high-resolution membership function is used in the range where the system error is relatively small or close to zero. Compared with Gaussian curve, trigonometric function curve has a concentrated distribution of fuzzy variables in fuzzy subsets for systematic errors, while trigonometric function curve can evenly distribute fuzzy variables in fuzzy subsets and is sensitive to system error changes. Given the superior performance of the fractional-order PID controller and the small system error, the membership functions of the input and output variables are selected as triangles, and the membership function curves of the input and output variables are shown in Fig. 15 and 16.

The core of fuzzy controller is to build fuzzy rule base, and the performance of controller depends on its accuracy. The design of fuzzy rules mainly refers to the knowledge and experience accumulated by operators and experts. In addition, factors such as actual heating, system reaction time and overshooting in the heating stage should also be considered comprehensively. By analyzing the temperature rise characteristics of the liquid and

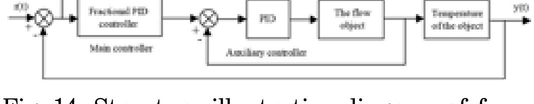


Fig. 14. Structure illustrative diagram of fuzzy fractional order PID control system.

the influence of the three parameters in the fractional PID controller, the setting rules of the three parameters were obtained as shown in Table 2.

Based on the above analysis and the research and investigation of the pulping workshop, the long-term accumulated experience and knowledge of pulping technicians and engineers were summarized, and the fuzzy control rules for the three parameters of the fractional PID controller were developed, as shown in Table 3. According to the fuzzy rule base, its reasoning form was: If E is PS and EC is NM, then Δkp is PS, Δki is NS, and Δkd is Z.

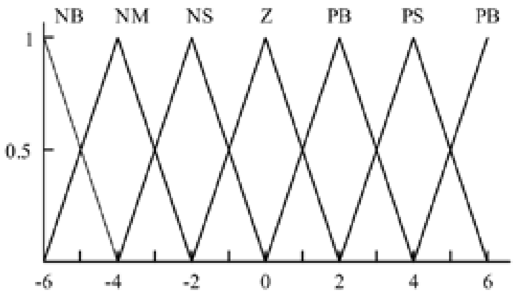


Fig. 15. Membership function curve of various e, Δkp, Δkd.

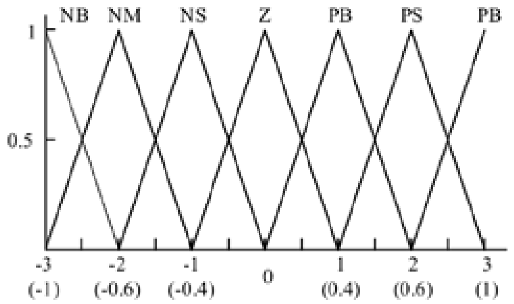


Fig. 16. Membership function curve of input variable ec (output variable Δki).

The output variable after fuzzy reasoning was a kind of fuzzy value, which could not be recognized by the affected object. Therefore, the process of fuzzy output variable precision was called defuzzification or defuzzification. The fuzzy fractional PID controller designed in this paper adopted the centroid method to clear the fuzzy inference result. The discrete expression of the barycenter method is:

$$u_0 = \frac{\sum_{i=1}^{m} k_i \mu(k_i)}{\sum_{k=1}^{m} \mu(k_i)} \qquad [14]$$

3.3 Comparison of different control system

Under the same experimental conditions, fuzzy fractional PID was used to control the temperature of the liquid in the cooking pot. The temperature

Table 2. kp, ki, kd parameter setting rule table

	kp	*ki*	*kd*
$\lvert e \rvert$ larger	Larger value	Smaller values	Smaller values
$\lvert e \rvert$ medium	Smaller values	moderate	moderate
$\lvert e \rvert$ smaller	Larger value	Larger value	Smaller values

Table 3. Δkp, Δki, Δkd fuzzy control rule

$\Delta kp/\Delta ki/\Delta kd$		*e*						
		NB	NM	NS	Z	PS	PM	PB
ec	NB	PB/NB/PS	PM/NB/Z	PM/NM/Z	PM/NM/Z	PS/NS/Z	PS/Z/PB	Z/Z/PB
	NM	PM/NB/NS	PM/NM/NS	PM/NM/NS	PM/NS/NS	PS/NS/Z	Z/Z/NS	Z/Z/PM
	NS	PM/NM/NB	PM/NM/NB	PS/NS/NM	PS/NS/NS	Z/Z/Z	Z/Z/Z	NS/PS/PM
	Z	PM/NS/NB	PS/NS/NM	PS/NS/NM	Z/Z/NS	NS/Z/Z	NS/PS/PS	NS/PS/PM
	PS	PS/NS/NB	PS/NS/NM	Z/Z/NS	NS/PS/NS	NS/PS/Z	NM/PM/PS	NM/PM/PM
	PM	Z/Z/NM	Z/Z/NS	NS/PS/NS	NM/PS/NS	NM/PM/Z	NM/PM/PS	NM/PB/PS
	PB	Z/Z/PS	NS/Z/Z	NS/PS/Z	NM/PM/Z	NM/PM/Z	NM/PB/PS	NB/PB/PM

data of the process was collected by Matlab and compared with the traditional PID control. During the experiment, when the temperature of the liquid reached 150℃ in the middle cooking stage, the medium pressure steam valve was set to open, and the temperature of the liquid in the cooking pot was controlled. The final cooking temperature was maintained at about 165℃, as shown in Fig. 17. The performance indexes of different control strategies are shown in Table 4.

It can be seen from the figure that the temperature of liquid medicine controlled by traditional PID reaches the highest 169.7℃, while the temperature controlled by fuzzy fractional PID reaches the highest 167.3℃. Although the temperature of liquid medicine controlled by traditional PID is fast and the curve slope is large, the adjustment time is long and the temperature of top and lower part of the pot is easy to be too high. Although the temperature rise of liquid medicine controlled by fuzzy

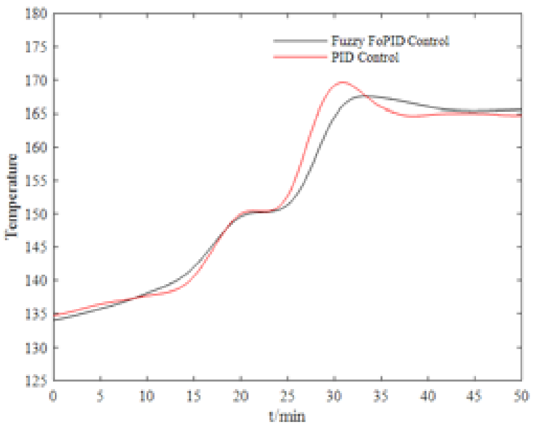


Fig. 17. Temperature rise curves of different control strategies.

Table 4. Performance indicators of different control strategies

Methods	M_p/%	t_s/s
Fuzzy–FOPID	2.1	840
PID	2.84	960

In the table, M_p means the overshoot of the system; t_s means the adjustment time of the system.

fractional PID is relatively slow, the whole heating process is stable, without large overshoot and fast adjustment speed, and it is not easy to cause the local temperature in the pot to be too large.

4. Conclusions

In this paper, firstly, the temperature rise mechanism of the cooking liquid was analyzed through DDS cooking process, and the temperature object of the cooking liquid was determined to have time–delay and nonlinear characteristics. Then, combined with the technological process, a cascade control loop was formed with the temperature of the cooking pot as the main control object and the liquid flow control as the secondary control object. The temperature rise curve of liquid medicine controlled by PID was measured by experiment. Aiming at the time–delay and nonlinear problems existing in the temperature rising process of cooking liquid, a fuzzy fractional PID controller was designed. Experiments were conducted on the temperature rising process of liquid cooking liquid, and a comparative analysis was made with the traditional PID control method. Finally, conclusions were drawn as follows:

1) There is a large overshoot in the temperature rising process of liquid medicine controlled by traditional PID, which is easy to cause the local temperature in the cooking pot to be too high, which is not conducive to the temperature uniformity of all parts in the cooking pot.
2) The temperature rise curve of liquid medicine controlled by fuzzy fractional PID is more stable, the adjustment process is faster, and it is not easy to cause large temperature difference between top and lower parts.
3) It is proved that the fuzzy fractional PID cascade control strategy can effectively improve the stability of the liquid temperature control

system, meet the requirements of temperature control, and achieve better control effect.

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Literature Cited

1. Sheoran, M., Goswami, S., and Pant, H.J., Measurement of residence time distribution of liquid phase in an industrial–scale continuous pulp digester using radiotracer technique, Applied Radiation and Isotopes, 111:10–17 (2016).
2. Kesavan, P., Lee, J.H., and Saucedo, V., Partial least squares (PLS) based monitoring and control of batch digesters, Journal of Process Control, 10: 229–236 (2000).
3. Belarbi, K., Bettou, K., and Mezaache, A., Fuzzy neural networks for estimation and fuzzy controller design: simulation study for a pulp batch digester, Journal of Process Control, 10(35): 35–41 (2000).
4. Leiviskä, K., Elman Network in Kappa Number Prediction, IFAC Proceedings Volumes, 42(01): 477–482 (2009).
5. De Vaal, P. and Sandrock, C., Control of a batch pulp digester using a simplified mechanistic model to predict degree of polymerization, Computers and Chemical Engineering, 31(10): 1222–1230 (2007).
6. Shan, H. L., Wang, W. H., and Sun, Y. X., Overview of soft measurement modeling for batch cooking process, Chinese Journal of Papermaking, 18 (02): 199–204 (2003).
7. Tang, W., Yu, D. W., and Zhang, Y. Z., Research on Soft Measurement Modeling of Displacement Cooking End Point Based on Recursive PLS, Chinese Journal of Papermaking, 30 (03): 47–50 (2015).
8. Yüce, A., Tan, N., and Atherton, D.P., Fractional Order PI Controller Design for Time Delay Systems, IFAC–Papers Online, 49(10): 94–99 (2016).
9. Shah, P., and Agashe, S., Review of fractional PID controller, Mechatronics, 38(01): 29–41 (2016).
10. Shan, W. J., Tang, W., and Wang, M. X., Application of Neural Network Fractional PID Controller in Pulp Concentration Control, Chinese Journal of Papermaking, 31 (04): 44–48 (2016).
11. Haji Haji, V., and Monje, C.A., Fractional order fuzzy–PID control of a combined cycle power plant using Particle Swarm Optimization algorithm with an improved dynamic parameters selection, Applied Soft Computing, 58: 256–264 (2017).
12. Liu, L., Pan, F., and Xue, D., Variable–order fuzzy fractional PID controller, ISA Trans, 55: 227–233 (2015).
13. Liu, H. B., Automatic measurement and control of pulping and papermaking process, China Light Industry Press, Beijing, pp. 21–27 (2009).
14. Oustaloup, A., Moreau, X., and Nouillant, M., The CRONE suspension, Control Engineering Practice, 4(8): 1101–1108 (1996).
15. Xue, D. Y., Zhao, C. N., and Chen, Y. Q., A Modified Approximation Method of Fractional Order System, IEEE International Conference on Mechatronics and Automation, 20: 1043–1048 (2016).
16. Xue, D. Y., and Chen, Y. Q., MATLAB For Solving Advanced Applied Mathematical Problems, Tsinghua University Press, China, pp.

434–450 (2013).
17. Zheng Y. J., Bai, W., and Xue, S. H., SIMULINK Implementation of fractional order Transfer Function, Control Engineering, 20 (06): 1066–1069 (2013).
18. Tepljakov, A., Petlenkov, E., and Belikovl, J., Design of retuning fractional PID controllers for a closed-loop magnetic levitation control system, 2014 13th International Conference on Control Automation Robotics & Vision (ICARCV), Singapore, pp. 1345–1350 (2014).
19. Yüce, A., Tan, N., and Atherton, D.P., Fractional Order PI Controller Design for Time Delay Systems, IFAC-Papers Online, 49(10): 94–99 (2016).
20. Taonian, L., Fractional PID controller and stability domain analysis of fractional order system with uncertain parameters, Ph.D. Thesis, Xidian University, Xi 'an (2011).
21. Liu, P., and Yuan, X., Performance analysis of Oustaloup rational approximation of ideal fractional resistance, Advanced Engineering Sciences, 48(S2): 147–154 (2016).
22. Zhao, X. Y., Research on Improved Oustaloup Digital Realization Algorithm, Science and Technology Information, (24): 7–8 (2013).
23. Gao, Z., Liao, X. Z., Improved Oustaloup approximation of fractional-order operators using adaptive chaotic particle swarm optimization, Journal of Systems Engineering and Electronics, 23(1): 145–153 (2012).
24. D. Valério, J. Sá da Costa. Variable-order fractional derivatives and their numerical approximations, Signal Processing, 91(3): 470–483 (2011).
25. Wang Z., Research and Implementation of Control Strategy of Dissolver Pulp Replacement Cooking Process, Master's Thesis, Shaanxi University of Science and Technology, Xi'an (2015).