Optimization of Combustion Control System for Regenerative Forging Heating Furnace

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Abstract. In order to reduce the influence of temperature fluctuation on heat treatment of regenerative forging reheating furnace, a scheme of improving traditional cascade PID controller to fuzzy PID controller was proposed in this paper. Taking the actual PID parameters of reheating furnace in forging workshop of a steel plant as reference object, the feasibility of the scheme is simulated by using MATLAB/SIMULINK. The results show that: 1) The control effect of fuzzy PID control is better than that of PID control in overshoot and adjusting time when the gain coefficient is perturbed 30%; 2) The dynamic performance of the system does not change significantly when the time constant is perturbed 20%; 3) The fuzzy PID shows better stability when the lag time is perturbed 20%.

1. Introduction
Regenerative forging heating furnace is a kind of equipment used in heat treatment process. The quality of heating performance directly affects the effect of heat treatment and the final product quality. In the stable production process of reheating furnace, the combustion control system controlled by PID can work well, but in the process of heating, the lag of the system is serious and the fluctuation of furnace temperature is large [1]. In order to ensure that the reheating furnace can be better suitable for heat treatment process, it is necessary to optimize the combustion control system.

According to different production processes, heating furnaces can be divided into continuous heating furnaces and chamber heating furnaces. The continuous heating furnaces are generally used in rolling workshop, while the forging workshop mostly uses chamber heating furnaces [2]. At present, scholars mostly take continuous reheating furnace as the research object to optimize the combustion control system. They usually adopt a new type of fuzzy PID control system based on PID control and assisted by fuzzy control. For example, Sun et al. [3] carried on the simulation research to the fuzzy PID temperature control system on the continuous heating furnace, Liu et al. [4] carried on the fuzzy PID control in the continuous steel rolling heating furnace the application; Li et al. [5] studied the technical plan to control the preheat and the exhaust temperature by the feedback of gas flow for continuous heating furnace. The case of applying fuzzy PID control system to chamber heating furnace has not been consulted. In this paper, the scheme of fuzzy-PID controller was applied to the chamber heating furnace, and the specific algorithm of fuzzy-PID control was given. The control system was simulated by using MATLAB/SIMULINK. The simulation results show that when the...
system is disturbed by external disturbances, the fuzzy PID combustion control scheme can effectively resist external disturbances and make the heating furnace in the optimal operation state.

2. Heating furnace and its combustion control system

A regenerative forging furnace is a chamber structure. The furnace size is 4800mm × 3850mm × 1573 mm, the effective heating zone is 4300mm × 3500mm × 550mm, and the maximum loading mass is 25000 kg. There are 10 regenerative burners arranged on both sides of the furnace body. Each regenerative burner is equipped with a three-way reversing valve, a total of 10 three-way reversing valves. During the heating process, the burners on both sides work in pairs, one side work in the combustion state, the other side are in the smoke exhaust state. The regenerator of regenerative burner is honeycomb ceramic. The regenerator is divided into five rows. The first three rows are made of mullite and the last two rows are cordierite. When the regenerative burner is in the state of exhaust gas, the regenerator can fully absorb the heat in the flue gas, so that the exhaust gas temperature is lower than 150°C; when the regenerative burner is in the state of combustion, the room temperature air flowing through the regenerator can absorb the heat of the regenerator, so that the combustion air is preheated to 100~200°C lower than the furnace temperature, and the heat released by gas combustion can be fully utilized.

![Block diagram of combustion control system for regenerative forging heating furnace](image)

Figure 1. Block diagram of combustion control system for regenerative forging heating furnace

The structure of combustion control system of regenerative forging heating furnace is shown in Fig. 1. The original system shown in Fig.1 (a) adopts traditional PID mode to control furnace
temperature. The furnace temperature control is the main controller loop, the gas and air controller is the sub-controller loop, and the total cascade combustion control system is formed in series. The quality of the control system depends on the setting of three parameters of P, I and D in each controller. In order to avoid the influence of excessive disturbance on furnace temperature stability, a heating furnace control scheme based on fuzzy PID control theory is proposed. The structure of the modified control system is shown in Fig. 1 (b), in which the virtual frame is a fuzzy PID controller.

3. Design of Fuzzy PID Controller

Fig. 2 is the structure of the fuzzy PID controller. Fig. 2 shows that \( K_{ec} \) and \( K_e \) are the quantization factors of the fuzzy control variables, and their values will affect the regulation performance of the control system. The adjusting speed of the control system increases with the increase of the value of the quantization factor \( K_e \), but \( K_e \) is too large, the system will overshoot or even oscillate; otherwise, the adjusting speed of the control system will decrease with the decrease of the value of the quantization factor \( K_{ec} \), and \( K_e \) is too small, the stability of the system will decrease. Similarly, the value of quantization factor \( K_{ec} \) also affects the performance of the control system, but its effect is opposite.

![Figure 2. Fuzzy PID control principle diagram](image)

Fuzzy PID controller takes the deviation \( e \) and deviation change rate \( ec \) of furnace temperature setting value \( s \) and measured value \( r \) as input signal, and outputs \( \Delta K_p \), \( \Delta K_i \) and \( \Delta K_d \) after fuzzification and fuzzy inference, which calculates with \( K_p \), \( K_i \) and \( K_d \) parameters of cascade furnace temperature PID controller to ensure that the heating furnace is always in the optimal state.

The basic domain of deviation \( e \) of fuzzy PID controller is \([-14,14]\), and the basic domain of deviation change rate is \([-25,25]\). The fuzzy domain of deviation input variable \( E \) and deviation change rate \( EC \) is \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\}, and the output is \( \Delta K_p \), \( \Delta K_i \), \( \Delta K_d \). The quantification factor \( K_e=6/14=0.429 \) and \( K_{ec}=6/25=0.24 \) are determined according to the values of the basic and fuzzy fields of the input quantity.

In the process of fuzzification, it is necessary to establish a fuzzy subset and determine the membership function of input and output. Generally, NB is negative large, NM is negative medium, NS is negative small, ZO is zero, PS is positive small, PM is positive medium, PB is positive large, then the fuzzy subset can be denoted as \{NB, NM, NS, ZO, PS, PM, PB\}. The stability of the control system is determined by the membership function. The control system is stable when the membership function is gentle, and the sensitivity of the system is high when the membership function is steep [6]. In view of the small size of the furnace body and the uniform temperature distribution in the furnace, in order to simplify the control algorithm of fuzzy PID, the membership functions of \( e \), \( Ke \) and \( \Delta K_p \), \( \Delta K_i \) and \( \Delta K_d \) are selected as triangular membership functions, as shown in Formula 1.

\[
 f(x, a, b, c) = \begin{cases} 
 \frac{x-a}{b-a}, & b \leq x \leq a \\
 \frac{c-x}{c-a}, & a < x \leq c \\
 0, & x < b \text{ or } x > c 
\end{cases}
\]

where: \( a \), \( b \) and \( c \) are the lengths of the three sides of a triangular function.
The design of the fuzzy rules should not only consider the actual working condition of the furnace, but also take into account the response time, overshoot and final steady-state error of the furnace temperature control system. According to the relationship between three parameters $K_p$, $K_i$, $K_d$ of PID control and input deviation $e$ and deviation change rate $ec$, and combined with the experience of relevant experts, a fuzzy rule table is established, which takes $e$ and $ec$ as input variables and $ΔK_p$, $ΔK_i$ and $ΔK_d$ as output variables.

The process of clarification of fuzzy variables is as follows: firstly, $e$ and $ec$ are arranged and combined, secondly, the corresponding output is estimated for each combination, and then the query table of output variables is established and stored in the system. When the control variable generates input, it can be quantified and transformed into elements in the universe. Then the output value and scaling factor operation can be obtained from the query table to get the accurate output.

$L_1$, $L_2$ and $L_3$ are respectively used to represent the fuzzy control relations contained in each fuzzy statement. The fuzzy control rules can synthesize all the fuzzy relations into the total fuzzy relations $L$ as follows:

$$L = L_1 \cup L_2 \cdots \cdots \cup L_3 = L_{i=1}^n$$

By using the fuzzy relation $L$, $ΔK_p$ can be calculated according to the fuzziness of the input deviation $e$ and the fuzziness of the deviation change rate $ec$, and then the fuzziness can be defuzzified to get the query table of the output value $ΔK_p$. Similarly, the query tables of $ΔK_i$ and $ΔK_d$ can be obtained.

4. Simulation comparison of two control methods

According to the repeated debugging in actual production, the optimal value scheme of cascade PID control system is $K_p=9.5$, $K_i=0.2$, $K_d=11$ for the main controller of furnace temperature, $K_p=0.16$, $K_i=0.12$ for the gas flow controller, $K_p=0.14$ and $K_i=0.11$ for the air flow controller.

Combining the fuzzy controller with the traditional PID controller, the combustion control system of the heating furnace is established. The system simulation is carried out by using MATLAB/SIMULINK. The simulation model of the system is shown in Fig. 3. Furnace temperature transfer function is a function of first-order inertial lag, while the transfer function of natural gas and air is a first-order inertial system without delay. In the simulation system, the transfer function of furnace temperature is $G(s)=\frac{8}{(140s+1)}e^{-60s}$, the gas transfer function is $G(s)=\frac{1}{(20s+1)}$, and the air transfer function is $G(s)=\frac{1}{(65s+1)}$.

Figure 3. Fuzzy PID simulation diagram using MATLAB/SIMULINK
Fig. 4 is a simulation comparison of the two control schemes. Assuming that the furnace temperature has reached a stable value in the initial state, the set value of the furnace temperature will be increased 50°C at t=0. Fig. 4 (a) shows the presetting parameter state of the fuzzy PID and PID. It is obvious that the performance of the fuzzy PID control is superior to that of the PID control. Fig. 4 (b) shows that the control effect of fuzzy PID control is better than that of PID control in overshoot and adjusting time when the gain coefficient is changed by 30%. Fig. 4 (c) shows that the dynamic performance of the system does not change significantly when the time constant is perturbed by 20%. Fig. 4 (d) shows that the lag time perturbation is 20%, and the fuzzy PID shows better stability. The above simulation results show that the proposed fuzzy PID control has better control effect than the original traditional PID control.

5. Conclusion
According to the actual working condition of regenerative reheating furnace, a scheme of improving traditional cascade PID controller to fuzzy PID controller was proposed. Based on the working principle of the heating furnace and the characteristics of the heating object, a fuzzy PID controller was designed. The feasibility of the intelligent control system of the fuzzy PID heating furnace was studied by using MATLAB/SIMULINK. The results show that the control effect of the control system is much better than that of the traditional control scheme. The response speed and dynamic performance of the control strategy are obviously improved. Therefore, the system has the value of further research for thermal process control.

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