A Self-tuning Fuzzy PID Control Method of Grate Cooler Pressure Based on Kalman Filter

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Abstract. A self-tuning fuzzy PID control method of grate cooler pressure based on Kalman filter was developed to overcome the frequently varying working condition and worse signal-to-noise radio of pressure signals. Based on dynamic simulation and characteristics analysis on clinker cooling system, the system variables were determined, then the control model of grate cooler was obtained by system identification. It was shown that this method could inhibit the influence of noise of pressure signals, could enhanced adaptive capability of controller and could improved heat energy recovery efficiency of grate cooler.

Keywords: self-tuning fuzzy PID, Kalman filter, grate cooler

1. Introduction

Clinker cooling process is the key process in cement production which cool hot clinker and recycle heat energy. Therefore, the stable control of clinker cooling process plays a key role to keep production quantity and reduce energy resume. As the important parameter, grate cooler pressure represents the balance relationship between hot material and cool air, and influences the effect of clinker cooling and heat recovery[1].

The desire to control grate cooler pressure has motivated extensive research on clinker cooling process. Wu developed gray model of grate cooler, then predictive control was used to cooling process[2]. A fuzzy predictive method was introduced to resolve the coordination of grate cooler, which adapted to the system with more output variables than input variables[3]. Wardana proposed a PID-fuzzy controller for grate cooler. The proportional, integral and derivative constant adjusted by new rule of fuzzy to adapt with the extreme condition of process[4]. However, actually we cannot obtain the true signal of grate cooler pressure due to frequently varying working condition and worse noise. Motivated by the above, in this paper, we focus on process mechanical and dynamic character analysis, then provide the self-tuning fuzzy PID control scheme of grate pressure based on kalman filter.

Our study extends previous work in several respects. Firstly, a self-tuning fuzzy PID approach based on Kalman filter is advanced in order to adjust the pressure under the grate cooler. Secondly, based on dynamic simulation and characteristics analysis on clinker cooling system, the system variables were determined, then the control model of grate cooler was obtained by system identification. Finaly,it was found that this method could inhibit the influence of noise of pressure signals, could enhanced adaptive capability of controller and could improved heat energy recovery efficiency of grate cooler.

The structure of the paper is as follows. Section 2 describes the process and analyzes the dynamic characters. Section 3 introduces the control scheme design. Section 4 presents the industrial experement in cement plant. Section 5 is a brief conclusion of the paper.

2. Process Description and Analysis

Cement clinker cooling process takes place in grate cooler, as can be seen from Fig. 1. The hot clinker leaving the kiln falles into grate cooler where they encounter the cold air and transfer heat to the air. The heated air actes as the second air and third air to kiln and calciner respectively. This process not only improves fuel efficiency but also saves heat energy. Finally, the qualified clinker is crushed and sent to storage.

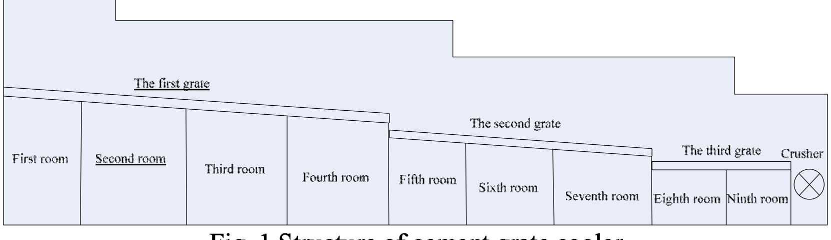

Fig. 1 Structure of cement grate cooler

The cooling effect of clinker is affected directly by the clinker thickness in grate cooler. Usually we adjust the clinker thickness by grate speed. But the clinker thickness has not direct detection in practice. The pressure under the grate of the cooler is monitored and is taken to be directly proportional to the thickness of the bed of clinker on the grate. According to operation requirements, the second room pressure is adjusted by the first grate speed. When the first grate speed becomes slow, the load of clinker entering the cooler thickens the bed and the pressure under the grate rises. Conversely, the first grate speed becomes fast, the clinker bed thins out and the pressure under the grate falls.

Next, a step change of the first grate speed is imposed and we obtain the trend of the pressure based on dynamic model of clink cooling model [5].

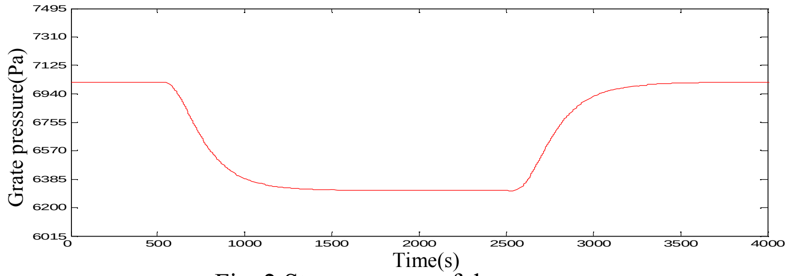

Fig. 2 Step response of the pressure

Firstly, the grate speed is increased by10% from 420rpm, then droped 10%. When the grate speed increased, the pressure droped soon(see Fig. 2). The reason is that the grate pushes the clinker forward faster, then the thickness of bed becomes thiner and the resistance of cold air becomes less. As can be seen that the lag time is not very large in the curve, but the transition process has a little long duration. Therefore, the process has high inertia.

According to the analysis of step response, the transfer function can be expressed as

$$G_p\ s = \frac{18.75}{496s+1}\cdot e^{-60s}. \qquad (1)$$

3. Control Scheme Design

In this paper a self-tuning fuzzy PID control scheme based on kalman filter is presented. The parameters of controller can adapt to frequently varying working condition and the filter can eliminate the influence of worse noise. The control structure is shown in Fig.3.

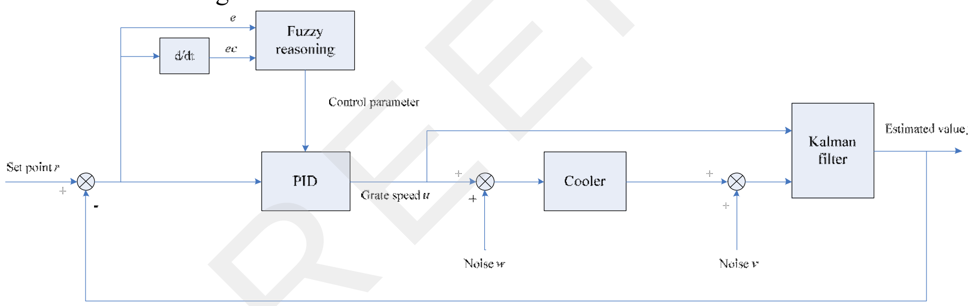

Figure 3 Grate cooler pressure self-tuning fuzzy PID control structure based on Kalman filter

In this scheme the second room pressure under the grate is the controlled variable and the first stage grate speed is the manipulate variable. The estimated value of the pressure is feedback signal for closed-loop control. In addition, fuzzy reasoning method is used to adjust the parameters of PID controller in order to improve system robustness.

A.Kalman Filter.

Kalman filter is used in various field of applications for optimal state estimation, noise filtering and prediction. A brief introduction to a kalman filter is stated as follows:

Assume that the evolution of the underlying signals to be observed can be modeled as

$$x(k+1) = Ax(k) + Bu(k) + w(k). \qquad (2)$$

$$y_v(k) = Cx(k) + v(k). \qquad (3)$$

Where $x(k)$ is the state at time k, A is the state transition matrix, B is the input transition matrix, $u(k)$ is the grate speed, $y_v(k)$ is the pressure signal with noise, and additive noise terms are included in the process $w(k)$ and measurement $v(k)$, their covariances are respectively Q_w and Q_v.

The discrete Kalman filter equations to estimate the state $x(k)$ are given as the following equations[6,7]. The symbols (-) and (+)used below represent the prior and updated value based on the use of the current measurement.

State estimate extrapolation

$$\hat{x}_{k(-)} = A\hat{x}_{k-1(+)} + Bu_k. \qquad (4)$$

Error covariance extrapolation

$$P_{k(-)} = AP_{k-1(+)}A^T + Q_w. \qquad (5)$$

Kalman gain matrix

$$K_k = P_{k(-)}C^T(CP_{k(-)}C^T + Q_r). \qquad (6)$$

State estimate update

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k(y_k - C\hat{x}_{k(-)}). \qquad (7)$$

Error covariance update

$$P_{k(+)} = (I - K_k C) P_{k(-)} . \quad (8)$$

Finally the estimated value of the pressure as

$$y_e(k) = Cx(k) . \quad (9)$$

B. Self-tuning fuzzy PID Control.

The fuzzy PID can adapt to the dynamics of the process better than the conventional PID controller[8]. In this paper, we use a self-tuning fuzzy PID method to adjust the pressure under the grate. The input variables are the error *e* and *ec* which is obtained from the difference of the setting value and estimated value of the pressure. Finally, the requirement of the dynamic and static performance are both satisfied by online adjusting the parameters of PID controller.

The self-tuning of PID parameters must consider two factors,one is the interaction and relationship among the three parameters at different times, and the other is the adjustment of parameters,such as polarity and magnitude. According to practical experience the adjustment fuzzy rules sheet are established (see Tab.1, Tab.2 and Tab.3).

Tab.1 Fuzzy rules sheet of k_p

e \ ec (k_p)	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PS	PS	ZO	NS
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PM	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Tab.2 Fuzzy rules sheet of k_i

e \ ec (k_i)	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Tab.3 Fuzzy rules sheet of k_d

e \ ec (k_d)	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

According to the rules sheet, thePID parameters k_p,k_i,k_d can adjust online as following.

The range of the input variables *e* and *ec* is definite in the domain of fuzzy set.

$$e, ec = \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\} . \quad (10)$$

The corresponding fuzzy set is $e, ec = \{\text{NB,NM,NS,ZO,PS,PM,PB}\}$. Where, the elements are respectively negative big, negative middle, negative small, zero, positive small, positive middle and positive big. Assume that *e*, *ec* and k_p, k_i, k_d are all gauss membership function.

According to the member function of fuzzy set and fuzzy control model, we obtain the accurate parameters $\triangle k_p$, $\triangle k_i$, $\triangle k_d$ of PID controller. Then we get the correction value of $\triangle k_p$, $\triangle k_i$, $\triangle k_d$ with the different combination of e and ec. These correction value presents with fuzzy matrix table which are $\{e_i, ec_i\}_p$, $\{e_i, ec_i\}_i$ and $\{e_i, ec_i\}_d$. These corrected parameters of PID controller calculate as follows.

$$
\begin{aligned}
k_p &= k_p' + \{e_i, ec_i\}_p \\
k_i &= k_i' + \{e_i, ec_i\}_i \\
k_d &= k_d' + \{e_i, ec_i\}_d
\end{aligned} \quad . \tag{11}
$$

Where, k_p', k_i' and k_d' are the initial values of PID parameters.

Finally, the calculation sequence of the self-tuning fuzzy PID method based on Kalman filter can be expressed as:

Step1: Give the initial parameters of Kalman filter and control algorithm;

Step2: Calculate the pressure under the grate by (4)~(9) and input-output data;

Step3: Update k times control value by self-tune fuzzy PID control algorithm;

Step4: Let k=k+1, and return Step2.

4. Industrial Experiment in Cement Plant

The control scheme in this paper was used at a new dry cement production line of Shanshui Cement Group Ltd. The specification of the production line as:

- Preheater two string 5 stage with precalciner
- Rotary kiln about 74 meters long
- Clinker cooler with grate hydraulic drive
- Total capacity 5000t/d clinker

The algorithm which is discribed in this paper is packaged in the self-definition function block and downloaded to DCS controller. The conventional PID and the algorithm discribed in this paper have been in operation successively at 320t/h working condition, and the control curve is shown as Fig.4. where, the parameters of the two algerithms are the same, k_p=0.8,k_i=0.05,k_d=2.5. It can be seen that the fluctuation magnitude droped down obviously after the algorithm proposed in this paper, and the error reduced by 51.5%.

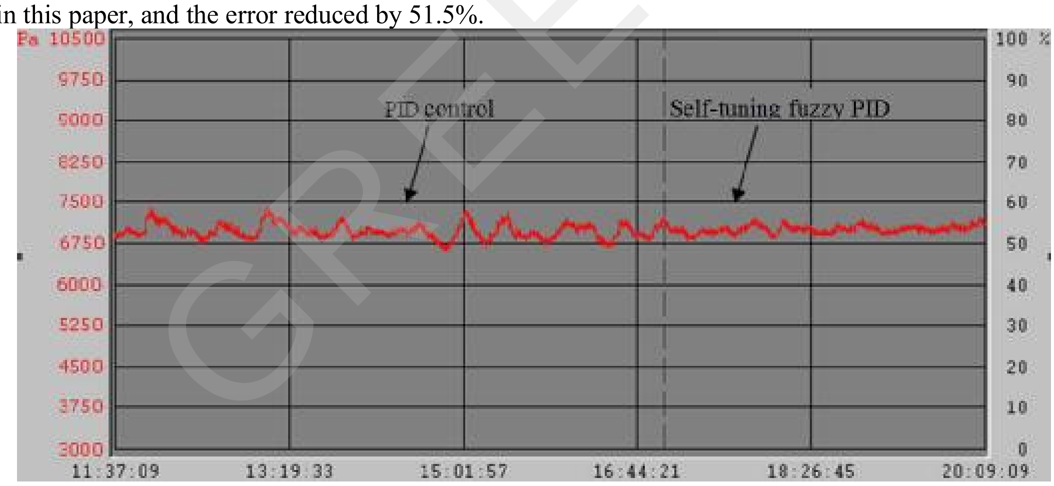

Fig.4 Trend of the pressure in second room under the grate

According to the experiment we can get the statistic data shown in Tab.4. During self-tuning fuzzy PID based ong Kalman filter was applied in operation with the grate cooler, we can observe the result that:

- The pressure under the grate was much more stable
- The temperature of clinker in outlet was further reduced
- The heat energy recovery efficiency increased

Tab.4 Statistics of operation data

	Operation time(h)	The pressure of second room grate (Pa)	Clink temperature in outlet(℃)	Average temperature of second air(℃)
PID	5	7106±475	97	997
Self-tuning fuzzy PID based on kalman filter	5	7156±182	91	1125

5. Conclusions

This paper presents a self-tuning fuzzy PID approach based on Kalman filter to adjust the pressure under the grate cooler. The heat recovery efficiency problem in cement plant has improved. Industrial experiment has proved that this approach not only has a good stability and robustness, but also has better energy efficiency. However, the long-term operation of the controller will be developed ulteriorly in the future.

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