Tobacco leaf redrying System Control based on Predictive Auto-Coupling PID

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Abstract. Temperature and moisture content in the process of threshing and re-drying can be defined as the same type of object, which is large time-delay with strong coupling. According to the present control strategy, the tobacco leaves control object (temperature and moisture content) occurs with large fluctuations due to the existence of uncertain disturbances. Therefore, the quality and reliability of the production is not good enough to keep the clients around. In order to improve the quality of export tobacco leaves. In this paper, Predictive Auto Coupling PID(PAC-PID) control algorithm is used to design controller for tobacco temperature and moisture content. The simulation results denote that the proposed method can smoothly track the desired signal with fast speed and high accuracy. Meanwhile, the control effect is better than the existing methods. We apply the control method to the actual production, the control effect shows that the stable time of the system is less than 16s, in the same time, the moisture content deviation of export tobacco leaves can be controlled within 1.5%. It means that the method can meet the actual production requirements

1. INTRODUCTION
Threshing and Re-drying is the key link in cigarette production, it’s main mission is to adjust the tobacco leaf moisture content, purify the tobacco leaves, remove the impurities, and kill the tobacco leaf pests and germs by controlling the temperature and humidity of the tobacco leaves. So it can achieve the purpose of conducive to the natural aging of tobacco leaves[1-3]. The stability of temperature and humidity during the re-drying process will directly affect the threshing and re-drying quality index, Therefore, the fluctuation of tobacco export quality can be reduced by effectively controlling the stability of tobacco export moisture and temperature, however, Because in the production process of threshing and re-drying, the tobacco processing machine has characteristics of complicated action process, a lot of influence factors, large reaction time and experience are highly dependent, it’s hard to build accurate mathematical models. In the existing control model, the PID control parameter setting value of tobacco processing machine and is totally dependent on the experience of field operators, so the control effect also dependent on the experience of field operators. that may lead to the unstable index of the control object, the accuracy is not high enough, even lead to unqualified products and return. In order to improve production efficiency, the control of tobacco production equipment is the focus of research. In recent years, the control algorithm that integrates traditional PID and intelligent algorithm has shown strong adaptability and solving ability in the temperature and humidity control of tobacco leaves.

Research paper[4-12] established a control model and designed a controller for the Chemistry and physics characteristics of tobacco temperature and humidity in the production of tobacco re-drying machines, paper[4-7]set up first-order plus time delay object base on characteristic of temperature
control object, and designed a predictive PI control rate to control the object. Simulation results show that the control effect can basically meet the production needs. Compared with the traditional PID control, the control accuracy is improved, but there is still a lot of room for improvement in the fast responsiveness. For tobacco leaf humidity objects, paper[4-8] established combined integral control model, using anti-delay quasi-PI control algorithm to design the controller, the control effect shows that the response of the controller is more sensitive, but the immunity is not good enough. Different from [4-8], Researcher[9-12] set up second-order oscillation model for tobacco leaf humidity objects, and used PI+Smith controller, simulation results shows that the controller's rapidity and immunity can meet the requirements of industrial production, but the controller needs to be adjusted with too many parameters. For producers with different tobacco leaf recipes, tuning the parameters of the controller is undoubtedly a big problem. In addition to the above research. Paper[13-17] proposed the fuzzy control algorithm in the production of threshing and re-drying, The experimental results show that relatively sound control effect, and the response speed and immunity meet the production requirements. But the disadvantage is that the formulation of fuzzy rules in fuzzy controller is based on the experience of on-site production personnel and relevant experts, that involves artificial subjective control factors, it’s hard to ensure that the same set of fuzzy rules can be applied to the entire production line system.

Predictive Auto Coupling PID(PAC-PID) is a control algorithm formed by combining the Auto Coupling-PID(AC-PID) and PI + Smith estimator. It inherit the Smith estimator's advance compensation for the system with time delay, At the same time, it also has the advantages of less parameter tuning, global robust stability and good anti-disturbance robustness of AC-PID, it has excellent tracking performance and disturbance recovery performance for long time-delay and strongly coupled objects.

In order to solve long-time delay, strong coupling object control problem, Based on the PAC-PID control principle, this paper designs PAC-PID controller for temperature and water content object, effect of various external disturbances on tobacco leaf quality was effectively inhibited. It is very hard to establish a strict mechanism model because of the complexity of the re-drying process.

2. TEMPERATURE AND HUMIDITY CONTROL OBJECTE
Threshing and re-drying is a long time-delay, strongly coupled, nonlinear and multi-interference process. The variation of factors in any region of different sections will affect the parameters and exit indexes of subsequent sections, Therefore, the establishment and design of process model and control object are particularly important. But the establishment of model and control object is the key to implement advanced control algorithm, the accuracy of the model is closely related to the quality of the control, especially temperature and humidity control object, In this paper, literature [4-12] is comprehensively summarized to determine the temperature and humidity objects in tobacco leaves.

For most industrial processes, temperature control is a process with long-time delay, threshing and re-drying is no exception. Based on the research results [4-7], it was found that, the mechanism of the temperature control object conforms to the first-order plus time delay model. Its transfer function is shown below:

\[ G_p(s) = \frac{K_p}{T s + 1} e^{-\tau s} \] (1)

In the transfer function(1), \( K_p \) mean the self-tuning proportionality coefficient of the control object, \( \tau \) means the time delay coefficient of the control object, \( T \) is the time constant of the control object, Take the actual situation into consideration. Temperature object transfer function parameter values: \( K_p = 1, \tau = 60s, T = 250s \).

According to the moisture mechanism analysis of tobacco leaves [6-10], the transfer function of the control object of tobacco leaf moisture content is as follows:

\[ G_p(s) = \frac{k_0}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau s} \] (2)
\( \tau \) means the time delay coefficient of the control object, \( T_1, T_2 \) is the time constant of the control object, \( K_0 \) is proportionality coefficient of the control object. Take into account the actual production situation, parameter values: \( k_0 = 1, \tau = 160 \text{s}, T_1 = 90 \text{s}, T_2 = 250 \text{s} \).

3. PREDICTIVE AUTO COUPLING PID CONTROLLER

3.1. Control system analysis

Because the temperature and humidity objects of tobacco leaf in re-drying production have the characteristics of strongly coupling and long-time delay. In this paper, PAC-PID algorithm is used to design the controller for the temperature and humidity control object of tobacco leaves, the design steps are as follows. As the transfer function of the control object (1) and (2) shows, the differential equation of the object is:

\[
\begin{align*}
\dot{y}_1 &= -ay_1 + bu + bd \\
\dot{y}_2 &= -a_0y_1 - a_1y_2 + bu + bd \\
y_p &= y_1(t - \tau) \\
y_p &= y_2(t - \tau)
\end{align*}
\]

The corresponding relation of model parameters of the system is shown in Table 1

| Table 1 Parameter correspondence |
|-----------------------------------|
| first-order system | \( a \) | \( 1/T \) |
| first-order system | \( b \) | \( K/T \) |
| Second-order systems | \( a_0 \) | \( 1/T_1T_2 \) |
| Second-order systems | \( a_1 \) | \( (T_1 + T_2)/(T_1T_2) \) |
| Second-order systems | \( b \) | \( K_0/T_1T_2 \) |

In the last parameters of the differential equation, \( d \) is the external bounded disturbance, \( u \) is the input of system, \( y_1, y_2 \) represents the internal system state, \( y_p \) is the output of system, suppose \( b = b_m + \Delta b \), \( b_m \neq 0 \) are rough estimates of the system model parameter \( b \), the total disturbance of a first-order system:

\[
\omega = -ay_1 + bd + \Delta bu
\]

The total disturbance of a second-order system:

\[
\omega = -ay_1 - a_1y_2 + bd + \Delta bu
\]

and \(|w| < \infty\), so (3), (4) can be expressed as:

\[
\begin{align*}
\dot{y}_1 &= w + b_m u \\
\dot{y}_p &= y_1(t - \tau) \\
\dot{y}_1 &= y_2 \\
\dot{y}_2 &= w + b_m u \\
y_p &= y_1(t - \tau)
\end{align*}
\]

Both (7) and (8) are uncertain systems with long time-delays, according to the characteristics of the system with long-time delay, when \( 0 \leq t \leq \tau \), the control object has no valid output, so \( y_p(t) = 0 \), and tracking error is:

\( e_1 = r \)

At this moment, the tracking error is at its maximum, but when the \( \tau \leq t \), the controlled object begins to transition to effective output, and \( y_p(t) = y_1(t - \tau) \), tracking error: \( e_1 = r - y_p \)
3.2. Smith predictive compensation controller

In order to solve the problem of large early error in tracking, we use smith predictive controller to compensate the system output. The first-order smith predictive controller:

\[ G_m(s) = \frac{b_m}{s+a_m} (1 - e^{-\tau_m s}) \]  

(9)

The second-order smith predictive controller:

\[ G_m(s) = \frac{b_m}{s^2 + a_{1m} s + a_{0m}} (1 - e^{-\tau_m s}) \]  

(10)

In the above two formulas, \( a_m, b_m, \tau_m, a_{1m}, a_{0m}, b_m, \tau_m \) is the estimated value of model parameter \( a, b, \tau \) and \( a_1, a_0, b, \tau \). So the differential equation of Smith estimator (9)-(10) is:

\[ \begin{align*}
\dot{y}_1m &= -a_my_1m + b_mu \\
y_m(t) &= y_1m(t - \tau_m) \\
y_1m &= y_2m \\
y_2m &= -a_{0m}y_1m - a_{1m}y_2m + b_mu \\
y_m &= y_1m(t - \tau_m)
\end{align*} \]  

(11, 12)

\( y_1m \) is the compensation output of Smith's prediction model under the action of \( u \) without time delay, \( y_m \) is the compensated output with time delay. Therefore, after the combining of (7), (8), (11) and (12), the prediction compensation link of the system is defined as:

\[ y(t) = y_p(t) + y_1m(t) - y_m(t) \]  

(13)

Assuming that \( \tau \approx \tau_m \), the predicted compensation output (13) can be divided into three cases:

(1) Case 1, when \( t < \tau \):

\[ \begin{align*}
\dot{y}_p(t) &= y_1(t - \tau) = 0 \\
y_m(t) &= y_1m(t - \tau) = 0
\end{align*} \]  

there has \( y(t) = y_1m(t) \), it means that predictive compensation output of the system is completely determined by the no-delay predictive model of smith controller (11)-(12), after that, the predictive compensation system, The first-order and second-order is shown in formula (14) and (15):

\[ \begin{align*}
\dot{y}_1m &= -a_my_1m + b_mu \\
y &= y_1m \\
y_1m &= y_2m \\
y_2m &= -a_{0m}y_1m - a_{1m}y_2m + b_mu \\
y &= y_1m
\end{align*} \]  

(14, 15)

(2) Case 2, \( T_t \) is adjusting time of the system. When \( \tau \leq t < T_t \), \( y_p(t) = y_1(t - \tau) \approx y_m(t) = y_1m(t - \tau) \), after combining (13):

\[ y_m(t) = y_1m(t) \]

(13)

(3) Case 3, when \( t \geq T_t \):

\[ \begin{align*}
\dot{y}_p(t) &= y_1(t - \tau) = y_m(t) \\
y_m(t) &= y_1m(t - \tau) = y_1m(t)
\end{align*} \]  

(13, 14, 15)

Base on (13), there has \( y(t) = y_p(t) = y_1(t) \), it means that the predictive compensation output of the system is completely determined by the inside state of the object with time-delay, the compensation output of Smith controller (11)-(12) completely cancels out, the system is totally transitioned to steady state.
The first-order: \[
\begin{aligned}
\dot{y}_1 &= w + b_m u \\
y &= y_p = y_1
\end{aligned}
\] (18)

The second-order: \[
\begin{aligned}
\dot{y}_2 &= w + b_m u \\
y &= y_p = y_1
\end{aligned}
\] (19)

It can be seen from the system (18) and (19) that the time-delay system has become a dynamic system without time delay after entering the steady state.

Base on the above three case, we can know, During the whole process control period of the system with time delay, the predictive compensation output of the system \(y(t)\) is determined by output of smith controller without time-delay: \(y = y_{1m}\) or the inside state of the object with time-delay: \(y = y_1\).

The inside state of system(16)-(17) is similar to System(18)-(19),but the disturbance range \(w\) of (18)-(19) is larger than(16)-(17). So system(16)-(17) is just A special column of System(18)-(19), Therefore, the internal dynamic system (18)-(19) can be taken as the controlled object for controller design.

3.3. Predictive Auto Coupling PID methods

Assumed anticipation error is \(y\), so the predictive compensation output of the control object is defined as: \(y(t) = y_p(t) + y_{1m}(t) - y_m(t)\),and tracking errors is defined as:

\[
e_1 = r - y = r - y_1
\] (20)

The error integration:

\[
e_0 = \int_0^t e_1(\eta) \, d\eta
\] (21)

The differential error:

\[
\begin{aligned}
e_2 &= e_1 = r - y = r - y_2 \\
e_2 &= r - y_2 = r - w - b_m u
\end{aligned}
\] (22)

According (20)-(22) can get the error dynamic system of first-order system is:

\[
\begin{aligned}
\dot{e} &= e_1 \\
\ddot{e} &= \ddot{r} - w - b_m u
\end{aligned}
\] (23)

Tuning rules of PAC-PI parameter selection:

\[
\begin{aligned}
K_p &= 2z_c \\
K_i &= z_c^2
\end{aligned}
\] (24)

The error dynamic system of second-order system is:

\[
\begin{aligned}
e_0 &= e_1 \\
e_2 &= e_2 \\
\dot{\ddot{e}} &= \ddot{r} - w - b_m u
\end{aligned}
\] (26)

Tuning rules of PAC-PID parameter selection:

\[
\begin{aligned}
K_p &= 3z_c^2 \\
K_i &= z_c^3 \\
K_d &= 3z_c
\end{aligned}
\] (27)

In the parameter setting principle, \(z_c > 0\) is the velocity factor of PAC-PID, \(z_c\) combines the physical elements with different attributes, such as proportion, integral and differential, to form a collaborative control signal.

According to the tracking errors system and tuning rules (23-27), PAC-PID is defined as:

First-order system:

\[
u = b_m^{-1}(\dot{r} + z_c^2 e_0 + 2z_c e_1)
\] (28)

Second-order system:

\[
u = b_m^{-1}(\dot{\ddot{r}} + z_c^3 e_0 + 3z_c^2 e_1 + 3z_c e_2)
\] (29)

The PAC-PID control principle diagram for the temperature and humidity control object of leaf-beating re-drying is shown in Figure 1 below.
Temperature and humidity control object

PAC-PID smith predictor

\[ e_1, e_2, e_3, e_4 \]

\[ \frac{1}{d/dt} \int_0^t e_1 \, dt \]

\[ Y_p \]

\[ Y_m \]

\[ \text{Temperature and humidity control object} \]

\[ \text{Smith predictor} \]

**Fig 1. PAC-PID control schematic**

In closed-loop control system that contains PAC-PID controller, the parameters to be tuned include: the parameters of estimator model \(a_m, b_m, \tau_m\), and the velocity factor \(z_c\) of PAC-PID.

Theoretically, in order to improve the response speed of the control system, \(z_c\) should be tuned bigger, but when \(z_c\) is tuned too much, system may cause overshoot and oscillations, because of the integral saturation problem at the initial stage of response. After research, we found that based on the time constant of the control object \(T_m\), Initial estimate of time delay \(\tau_m\) and Time delay online timing estimate \(\tau_0\) to tuning \(z_c\) can get better results[18]. The tuning rules as:

First-order: \[ z_c = \begin{cases} \frac{\alpha}{T_m + \tau_m}, & t < \tau_0 \\ \frac{\alpha}{\tau_m + \tau_0}, & t \geq \tau_0 \end{cases} \] (30)

Second-order: \[ z_c = \begin{cases} \frac{10a}{T_m + \tau_m}, & t < \tau_0 \\ \frac{10a}{\tau_m + \tau_0}, & t \geq \tau_0 \end{cases} \] (31)

In first-order system, \(a > 0\), When events occur that increase the time constant \(T\), \(a\) should be the minimum, Otherwise, take the opposite case. \(T_m\) is an estimate of the system time constant \(T\).

In second-order system, \(1 < a \leq 10\), When events occur that increase the time constant \(T\), \(a\) should be the minimum, Otherwise, take the opposite case, \(T_0\) is the transition time of the system into stable state.

Besides that, both initial estimate of time delay \(\tau_m\) and time delay online timing estimate \(\tau_0\) were needs to be get by follow:

\[ \begin{cases} \text{if \hspace{1cm} } Y(k) = 0, & t_x + t_x + t_s \\ \text{else} & \tau_0 = t_x \end{cases} \]

State observations will result in new delays, but the effects can be ignored, because it only adds one sampling period delay time on the basis of delay. In practical application, gain parameters in PAC-PID control are determined according to parameter tuning rules, and then fine-tuned according to specific indicators to get good control results.

**4. SIMULATION EXPERIMENT**

In order to verify the validity of PAC-PID in the process of tobacco leaf temperature and humidity object control, take the tobacco leaf temperature object (1) and the tobacco leaf humidity object (2) as an example to carry on the simulation comparison test.

**4.1. Temperature control object**

In the experiment, the desired trajectory is taken as the unit step signal. Sampling frequency: \(f_s = 1Hz\), step length: \(h = 1\), during simulation, the unit step disturbance is added in \(T=1500s\) to simulate the change of operating conditions. The proposed control results are compared with the control results of PI-Smith algorithm in paper [12] and Predictive PI algorithm in paper [4-7].

The parameter tuning of PAC-PID control is preliminarily selected as 3.2 according to rule (30), The PI-Smith control parameter tuning rule is set according to literature [12], while the predictive PI tuning rule is set according to literature [4-7].
It can be clearly observed from the comparison experiment in Figure 2, In the tobacco temperature object control process, PAC-PID algorithm can track faster and more accurately than PI-Smith and predictive PI; In the phase of disturbance rejection, the dynamic and steady-state effects of PAC-PID algorithm are significantly better than the other two controllers.

![Comparison of control effects of temperature objects](image)

(a) Comparison of step tracking results  (b) Comparison of disturbance immunity

Fig.2 Comparison of control effects of temperature objects

4.2. Humidity control object
The simulation experiment of tobacco humidity control adopts (2) as the control object model, the simulation experiment methods are PAC-PID, Predictive PID and Pi-Smith respectively. The parameters of PAC-PID controller are tuned according to rules (31), and the parameters of PI controller and PI+SMITH controller are set according to rules of paper[4-7] and [12]. The remaining parameters are adjusted adaptively according to the control object (2), the unit step disturbance is added in T=750s to simulate the change of operating conditions. It can be observed from the comparison test in Figure 3 that in the comparison of the control effects of the predictive PI and PI-Smith controllers for the humidity object, PAC-PID has better rapidity and ability against disturbances, overall control effects also better than the predictive PI and PI-Smith controllers.

![Comparison of control effects of temperature objects](image)

(a) Comparison of step tracking results  (b) Comparison of disturbance immunity

Fig.3 Comparison of control effects of temperature objects

4.3. Field production control effect
The PAC-PID controller was applied to line A of Changzhou Re-drying Factory for experimental verification. The actual production effect can be seen from Figure 4. The deviation between the actual value and the set value of moisture content after tobacco leaf moisture stabilization was 0.17, the value of deviation rate is 1.3%, the national standard for deviation rate is 3.0% [19], It is proved that PAC-PID controller has excellent accuracy control effect on tobacco humidity object.

It can be obtained by observing the moisture content curve of tobacco export. The moisture content of tobacco leaves rise to the peak of 13.1 within the time $t_p = 18s$, the overshoot of moisture content is 2.3%, under the action of PAC-PID controller, the stable value reached 12.82 rapidly after 24s, So system adjustment time $t_s = 42s$. At T=150s, the moisture content caused by disturbance fluctuates from 12.4 to 13.0, but under the control of the controller, the moisture content of tobacco leaves was...
adjusted back to the stable value only after 16s. It was proved that PAC-PID had the same excellent performance in the control of moisture content and disturbance resistance in the production process.

Fig. 4 Field production control effect

5. CONCLUSION
The temperature and humidity of tobacco leaves are controlled with large time delay and strong coupling in the process of leaf threshing and re-drying. Although many researchers have proposed excellent control algorithms for this subject, re-drying tobacco leaf is always a high-cost production process, and often a small carelessness will cause huge losses. However, the optimization of production control will also improve the production efficiency of re-drying. In the proposed paper, the characteristics of tobacco control object design in temperature and humidity mechanism is presented, which applied the large time-delay predictive auto-coupling PID control strategy (PAC-PID). With the comparison from the simulation results, the effect of PAC-PID method is better than that of the tradition ones, and it fulfils the requirement of all the current threshing and re-drying production. Finally, the control method is applied to the actual production, and the production results show that the control effect is excellent.

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