Research on Heating and Temperature Control System with Solid Electric Heat Storage Based on Improved Smith Predictive Control

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Abstract. In view of the hysteretic nature of the heating and temperature control system with solid electric heat storage, this paper intends to control the related equipment by improved Smith predictive control method relying on the solid energy storage heating demonstration project of a university. This control method adds an additional regulator to the Smith predictive control method; in this manner, it can appropriately reduce the sensitivity of model accuracy, enhance the adaptability and effectively overcome the influence of delay on system stability, thus creating better robustness. The experimental results indicated that the temperature control accuracy could reach ±1°C.

1. Introduction
Solid heat storage electric boiler, as an emerging form of heat source utilization, has attracted extensive attention, but there are still many problems in the control strategy due to its late start. Furthermore, in view of the great inertia, delay and nonlinearity of temperature control, traditional PID control could not easily achieve satisfactory results [1-2]. Even with a set of relatively ideal parameters, the working conditions and model of a solid heat storage boiler will continue to change during operation; therefore, it is hard to ensure the control quality.

Currently, there are many control methods for restraining time-delay, such as Smith predictive control, vague control, internal model control, predictive control, neural network and expert control [3]. Smith predictive control was proposed by American scholar Smith [4] for resolving the delay in the closed-loop characteristic equation of the time-delay system. Compared with conventional control, Smith predictive control can improve the control quality of the control system with the clear purpose and high control accuracy; however, it greatly relies on model accuracy, namely, when the model is mismatched, the control system would lead to oscillations due to poor robustness [5]. According to the characteristic of constant changing in working conditions of the solid heat storage electric boiler, in this paper, improved Smith predictive control is adopted to control the temperature of the related equipment.

2. Principle of the Improved Smith Predictor

2.1. Basic Principle of Smith Predictive Control
The basic idea of Smith predictive control is to estimate the dynamic model of the controlled object in advance, and then design a predictor for compensation, to make the controlled quantity delayed for $\tau$ fed back to the input terminal of the regulator in advance, making the regulator act in advance, so as to
reduce overshoot and accelerate the regulation process. The control system block diagram is shown in figure 1.

\[
\phi(s) = \frac{Y(s)}{X(s)} = \frac{G_c(s)G_0(s)e^{-\tau}}{1 + G_c(s)G_0(s)}
\]

As shown in equation (1), under the premise that the actually controlled object is completely consistent with the prediction model, \(e^{-\tau}\) is not included in the characteristic equation of the system, and the system performance is completely unaffected by the delay.

Smith predictive control theoretically eliminates the effects of time-delay on control quality. It can be seen that the stability of system control highly depends on accurate mathematical models, but it is generally difficult to obtain such models. Due to the incomplete knowledge and information about the controlled object, or deviations in the structure and parameter estimation caused by the complexity, the controlled model may be time-varying and uncertain, thus causing rapid deterioration and even oscillation of control characteristics of the system [6].

2.2. Adaptive Predictive Control of Dynamic Parameters
As for the heating and temperature control system with solid electric heat storage, it is difficult to obtain its precise mathematical model, and its object characteristics may vary with the change in running time. In view of the characteristics of such control objects, C.C.Hang proposed an improved Smith predictive control scheme - dynamic parameter adaptive predictive control [7]. It has one more regulator as compared with Smith predictive control, \(G_c2(s)\) (PI regulation is adopted under general conditions). The block diagram is shown in figure 2.

![Block diagram of the Smith predictive control system.](image1)

![Block diagram of improved Smith predictive control system.](image2)
As shown in figure 2, \( \hat{G}_0(s) \) is the estimation model without delay. Then the transfer functions are:

\[
Y(s) = \frac{G_{c1}(s)G_0(s)e^{-\tau s}}{1 + G_{c1}(s)\hat{G}_0(s) + G_{c1}(s)\frac{G_{c2}(s)\hat{G}_0(s)}{1 + G_{c2}(s)\hat{G}_0(s)}[G_0(s)e^{-\tau s} - \hat{G}_0(s)e^{-\tau s}]} \]  \hspace{1cm} (2)

\[
Y(s) = \frac{G_0(s)e^{-\tau s}}{1 + G_{c1}(s)\hat{G}_0(s) + G_{c1}(s)\frac{G_{c2}(s)\hat{G}_0(s)}{1 + G_{c2}(s)\hat{G}_0(s)}[G_0(s)e^{-\tau s} - \hat{G}_0(s)e^{-\tau s}]} \]  \hspace{1cm} (3)

As shown in equations (2) and (3), when \( \hat{G}_0(s) = G_0(s) \), namely when the model is completely accurate, the control effect is exactly the same as that of Smith predictive control as shown in figure 1, and the entire control system can be fully compensated; when \( \hat{G}_0(s) \neq G_0(s) \), through appropriate regulation of PI parameters \( K_{c2} \) and \( T_{i2} \) of the regulator \( G_{c2}(s) \), the sensitivity of the model accuracy can be reduced, and its robustness and stability can be enhanced.

3. Application Of Improved Smith Predictive Control In The Heating And Temperature Control System With Solid Electric Heat Storage

3.1. Process Of Heating with Solid Electric Heat Storage

This solid energy storage heating technology demonstration project integrates heat sources and heat exchange stations, which can store heat at night with off-peak electricity and perform water-to-air heat exchange with the fans and heat exchangers, for supplying heat to some buildings in the school. It actively responds to the national call of achieving the low carbon, environmental protection and pollution-free goal; in addition, it can also be taken as a teaching experiment platform with good operation monitoring images, to provide students with more extensive teaching experimental conditions.

The system process of heating with solid electric heat storage is shown in figure 3. The demonstration project consists of two 1.5MW heat accumulators, six variable frequency fans, four heat exchangers, two circulating pumps, two water make-up pumps, and sensors, etc. The heat exchangers can realize slow water-air heat exchange, so it is a system with large inertia and delay. The conventional PID control cannot guarantee the control quality, so the improved Smith predictive control is adopted to optimize the entire temperature control system.

Figure 3. System process of heating with solid electric heat storage.
3.2. Control Scheme and Logic
At night, the system stores heat with off-peak electricity, and PLC is used to control the circulating pump, the make-up pump and the fan by the set program and collected data, and monitor the operation of the control system, so as to ensure that the entire heating system can provide normal heating throughout the day.

The actuator in the control system is the fan, and the controlled object is the heat exchanger. The control structure is shown in figure 4.

In this control system, the improved Smith predictor is added to realize optimal control of the water supply temperature. Figure 4 can be converted into a block diagram of transfer functions (figure 5).

![Figure 4](image)

**Figure 4.** Block diagram of the heating and temperature control system with solid electric heat storage.

![Figure 5](image)

**Figure 5.** Block diagram of transfer functions of the heating and temperature control system with solid electric heat storage.

According to the Smith predictive control method, modeling should be performed for the controlled object, and the predictor should be designed to compensate the control system. The function expression is obtained:

\[
G_0(s) = G_1(s)G_2(s)G_3(s)G_4(s),
\]

first let

\[
G_0(s) = \frac{K_0}{(T_0s + 1)}e^{-\tau s},
\]

which is the typical first-order inertia plus delay.

3.3. System Modeling
To obtain the specific function expression of \( G_0(s) \), the step response experiment is performed in the control system with conventional PID as the controller, and then a response curve based on the output and water temperature is drawn according to the obtained experimental data; finally, the parameters of \( G_0(s) \) are determined by the identification method based on the response curve.

The experimental facilities for the step response experiment include the heat accumulator #2, fans #4-6 and heat exchangers #1-2. The power of the heat accumulator is 1.5WM, and that of the three fans is 5.5KW; the two heat exchangers are vacuum phase change heat exchangers, with the power of 330KW and 400KW.

Experimental scheme: Under the working conditions of the heat accumulator #2 at 350℃, increase the frequency of fans #4-6 to 25Hz from 20Hz, and establish a mathematical model based on the response process of water supply temperature.

After several experiments, the equivalent response curve is obtained, as shown in figure 6.
① Getting $K_0$

$$K_0 = \frac{y(x) - y(0)}{r} = \frac{7.86 - 0}{10} = 0.786$$

Where, $r$ = the percentage of input variation in the input range*100.

![Figure 6. Equivalent response curve.](image)

② Getting $T_0$ and $\tau_0$.

Take the points $(t_1, T_1) = (4.5, 5.7)$ and $(t_2, T_2) = (5.5, 7)$, and calculated by the two-point method:

$$M_1 = \ln \left(1 - \frac{T_1}{K_0r}\right) = \ln \left(1 - \frac{5.7}{7.86}\right) = -2.021$$

$$M_2 = \ln \left(1 - \frac{T_2}{K_0r}\right) = \ln \left(1 - \frac{7}{7.86}\right) = -2.213$$

$$\tau_0 = \frac{t_2M_1 - t_1M_2}{M_1 - M_2} = 2.544$$

$$T_0 = \frac{t_2 - t_1}{M_1 - M_2} = 5.208$$

Take $(t_1, T_1) = (3, 2.5)$ and $(t_2, T_2) = (4, 4.77)$ for calculation, $\tau_0 = 2.352$, $T_0 = 5.324$;

Take $(t_1, T_1) = (5, 6.5)$ and $(t_2, T_2) = (6, 5.7, 6)$ for repetitive computation, $\tau_0 = 2.633$, $T_0 = 5.189$.

Based on the mean of the three sets of data obtained above, $\tau_0 = 2.51$, $T_0 = 5.24$.

③ Determine the model:

According to the calculation results of ①②, substitute $K_0 = 0.786$, $\tau_0 = 2.51$, $T_0 = 5.24$ into $G_0(s)$, the system model is finally determined:
As shown in equation (4), \( \frac{\tau}{T} \approx 0.479 \). However, the dynamic characteristics of most controlled processes include both \( \tau \) and \( T \), the ratio \( \frac{\tau}{T} \) is generally used to measure the severity of delay of the controlled process. When \( \frac{\tau}{T} < 0.3 \), it is called a general delay process; when \( \frac{\tau}{T} > 0.3 \), it is called a big delay process. Therefore, the heating and temperature control system with solid electric heat storage is a big delay system, and conventional PID control cannot realize the optimal effect.

Therefore, improved Smith predictive control should be used to optimize the control of this system.

3.4. Control System Hardware and Software Design

As a heating technology demonstration project, there are a large number of analog and digital input and output points as compared with the normal heating project; therefore, three PLCs and one paperless recorder are selected. The three PLCs (one master and two slaves) are used to communicate through the Ethernet and perform coordinated control of the entire system; the paperless recorder records the collected data and calculation data in the internal storage system based on time, which can be displayed in various forms (such as numbers, bar graphs, and curves). At the same time, all data will be uploaded to the SCADA system of the host computer for data monitoring and storage, which can provide great convenience for the experiment process.

At the same time, the control system is also equipped with the WEINVIEW touch screen and ABB frequency converter. The touch panel of the WEINVIEW touch screen is equipped with a power isolator, which supports MPI 187.5K connection, and can be applied to 95% of the common PLCs, frequency converters, industrial computers and other marketed automation equipment; ABB frequency converter is simple in installation, setting and operation, and its stable performance and good dynamic characteristics can perfectly match the frequency conversion requirements of fans and water pumps, and stably and reliably meet the frequency conversion requirements of PID frequency output.

Partial interface of the touch screen is shown in figure 7.

PLC, the “brain” of the entire control system, adopts Siemens S7-200SMART, whose programming and debugging software STEP 7-Micro/Win provides a development function of simple PID control, and it also contains a PID tuning control panel that can monitor PID loop graphically. The superposition of output signals of two PID regulators can generate output signals of \( e^{-\pi} \), and then the entire Smith predictor can be completed based on the design of the classic PID controller [8-9].

Part of the software process is shown in figure 8.
Figure 7. Integrated management interface of touch screen.

Figure 8. Part of the software process.
4. Control Effect And Data Analysis

4.1. Control Effect

In order to verify the superiority of improved Smith predictive control compared with conventional PID control, it is necessary to collect the relevant data through experiments for comparative analysis. In order to avoid occasionality of experimental results, different working conditions should be selected for step response experiments, and the experimental data of the two methods should be compared and analyzed.

The parameters of conventional PID control have been determined as $K_p = 27$, $T_i = 420s$ through multiple experiments. The experimental results are shown below.

(1) Body temperature of the heat accumulator: 250℃.

The water supply temperature is set as 40℃, and Fans 4-6# are started for testing when the body temperature of the heat accumulator 2# reaches 250℃ and the actual water supply temperature reaches 30℃. The conventional PID control and Smith predictive control are respectively applied to the control system for testing. The results are shown in figure 9.

(2) Body temperature of the heat accumulator: 350℃.

The water supply temperature is set as 55℃, and Fans 4-6# are started for testing when the body temperature of the heat accumulator 2# reaches 350℃ and the actual water supply temperature reaches 45℃. The conventional PID control and Smith predictive control are respectively applied to the control system for testing. The results are shown in figure 10.

(3) Body temperature of the heat accumulator: 450℃.

The water supply temperature is set as 65℃, and Fans 4-6# are started for testing when the body temperature of the heat accumulator 2# reaches 450℃ and the actual water supply temperature reaches 55℃. The conventional PID control and Smith predictive control are respectively applied to the control system for testing. The results are shown in figure 11.
4.2. Data analysis
As shown in figure 9, 10 and 11, under the same working conditions and compared with the conventional PID control, improved Smith predictive control compensates for the delay effect of the system to a certain extent, and also controls the system overshoot within 5%, with the control accuracy of ±1℃; in addition, it also reduces the regulation time and greatly improves the oscillation amplitude of the control system. As indicated by the comparison, the improved Smith predictive control has strong adaptability to system interference, and can make the control system quickly, stably and accurately meet the control requirements.

5. Conclusion
After attaching the improved Smith predictor, the control effect of the temperature control system based on solid electric heat storage is significantly improved, with the control accuracy reaching ±1℃; it also reduces the overshoot and regulation time, and improves the anti-interference ability of the system. The experimental comparison indicated that the improved Smith predictive control could perform better in robustness and control quality than conventional PID control. This control method can be easily realized, and can better control the time delay system; therefore, it has great application value.

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