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Research on Post-Rolling Cooling System Temperature Control Based on Smith-Fuzzy PID

Yilong Yao[1,a], Zhao Zhang[1,b], Jianhui Shi[2,c,*], Ruquan Liang[2,d,*]

[1]School of Automation and Electrical Engineering, Linyi University, Linyi, China
[2]School of Mechanical and Vehicle Engineering, Linyi University, Linyi, China
[a]1263240345@qq.com, [b]2317018412@qq.com, [c]sjh051208@126.com, [d]tpjsli@163.com
[*]Corresponding author

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Abstract: The controlled cooling technology for hot-rolled strip steel is a critical factor in determining the quality and performance of finished steel products. The coiling temperature, as a key control parameter, directly impacts the stability of the post-rolling cooling system. To ensure precise temperature regulation of the steel plate during the cooling process after hot-rolled strip steel production and to address the challenges posed by system complexity and time delays, this paper introduces a control method utilizing a Smith Predictor integrated with a Fuzzy PID controller specifically for the post-rolling cooling system. First, Drawing from relevant temperature control experience and practical considerations, a mathematical model for the post-rolling cooling temperature control system was developed. Then, a PID temperature controller was designed using this model, with the PID parameters adaptively tuned via a fuzzy control algorithm. Additionally, the Smith predictor algorithm was introduced to compensate for system delay. Finally, a simulation model was developed using MATLAB's Simulink module, and comparative simulations were conducted. The results demonstrate that under Smith-Fuzzy PID control, the system exhibits minimal overshoot and steady-state error, the shortest settling time, enhanced stability, and overall improved control performance. The system shows strong adaptive capabilities in the post-rolling cooling process of hot-rolled strip steel, effectively achieving the desired steady-state characteristics.

1. Introduction

As the economy and production technology continue to advance rapidly, hot-rolled strip steel has become integral to various aspects of our daily lives. As the demand for higher quality steel products grows, the challenges of resource and energy shortages are becoming more pressing, making green manufacturing an urgent priority for the transformation and development of China's steel industry [1-3]. In this context, post-rolling cooling technology for hot-rolled strip steel, which emphasizes resource conservation and energy efficiency, has attracted significant attention from steel companies.

In recent years, the development of high-strength and specialized steel grades has led to stricter requirements for cooling technology, particularly in effectively controlling coiling temperature and ensuring uniform cooling. Accurate regulation of the coiling temperature is thus essential in the manufacturing process of hot-rolled strip steel.

In the actual cooling process, the factors influencing temperature are complex and variable. Currently, various methods are used to control temperature. Traditional PID control is easy to implement but difficult to optimize for the best parameters. While fuzzy control systems can handle large inertia, they may not meet precision requirements. To leverage the strengths and mitigate the weaknesses of both traditional PID controllers and fuzzy controllers, a combined approach is proposed. This method integrates fuzzy control with conventional PID control, designing a fuzzy PID controller that adaptively adjusts the PID parameters of the temperature control system through fuzzy reasoning [4].

Xiaoming Fan [5] tackled the issue of significant temperature variations between the head and tail of hot-rolled strip steel by implementing a fuzzy self-tuning PID controller for managing coiling temperatures. This approach, compared to conventional PID controllers, offers greater adaptability and robustness, effectively limiting temperature deviations to within 20℃ and significantly enhancing control accuracy. Weiwei Liu [6] enhanced the model's temperature control accuracy by integrating fuzzy control with traditional PID control in a feedback control system, which continuously corrected the deviation between the actual temperature measured by the coiling thermometer and the desired target temperature. This method also improved the model's adaptability. Hai Fang Wang [7] proposed an approach that combines PID and fuzzy control by developing a fuzzy adaptive PID controller based on fuzzy control rules. This controller allows for the online adaptive adjustment of the PID parameters. When applied to laminar cooling, the results showed that the fuzzy PID control exhibited strong applicability.

Fuzzy control is particularly advantageous for complex, nonlinear, and time-varying systems. However, in the post-rolling cooling process, there are inherent delays in heat conduction and the response of temperature measurement equipment as the steel plate cools from high temperatures to the target temperature, resulting in system lag. Pure fuzzy control is insufficient to handle these delays effectively. In industrial settings, the Smith predictor control is the most widely used technique to address pure delay issues.

Enyang Liu [8] created a feedback control approach utilizing a Smith predictor to enhance the precision of coiling temperature regulation. This method can quickly and stably adjust the coiling temperature within the required range when temperature deviations occur, demonstrating that the inclusion of a Smith predictor effectively suppresses the lag phenomenon in the post-rolling cooling system. Zhenlei Li [9] addressed the issue of feedback lag in temperature PID control by incorporating a Smith feedback control strategy with lag compensation, thereby eliminating the impact of lag on temperature control accuracy. By applying suitable feedback compensation within the Smith predictor control, it is possible to eliminate the pure delay present in the denominator of the closed-loop transfer function. Qin et al. [10] studied the high-precision temperature control of projection lenses with long thermal response times. They used a PID controller with a Smith predictor as the inner loop control algorithm to address the pure delay in the remote transmission of the cooling water circuit, achieving stable control performance and resolving significant system delays.

Given the complexities, nonlinearities, and significant delays in the post-rolling cooling system of hot-rolled strip steel, along with the limitations of traditional PID control for temperature regulation, this paper focuses on applying fuzzy control principles to perform self-tuning of PID parameters. Additionally, a Smith predictor is incorporated to enhance system stability. Simulations of the temperature control system are also conducted to evaluate the effectiveness of these approaches.

2. Design of Post-Rolling Cooling System

2.1. Establishment of Mathematical Model for Control System

Temperature control systems generally exhibit nonlinearity and considerable time delay. To simplify their mathematical representation, these systems are often approximated by either a first-order inertia with pure delay or a second-order system with pure delay. This paper specifically addresses the post-rolling cooling system and, to balance control dynamics with model complexity, employs a second-order transfer function incorporating delay elements to represent the mathematical model of the cooling control system.

The Figure 1 and Figure 2 show the temperature measurement results from two cooling experiments conducted on a 15mm steel plate.

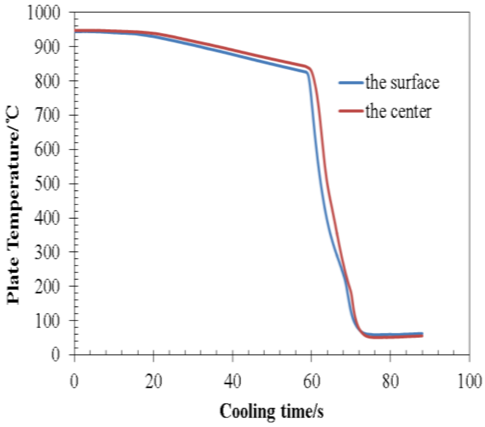

Figure 1: The first temperature measurement experiment.

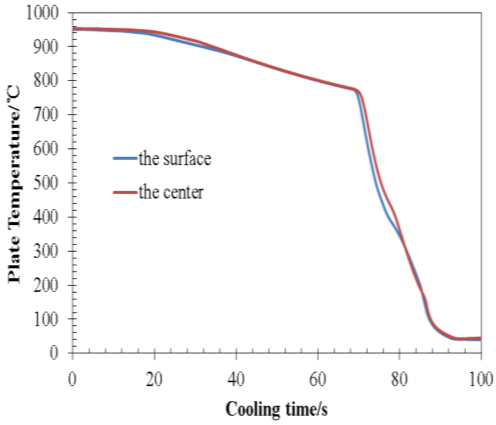

Figure 2: The second temperature measurement experiment.

Using experimental data from cooling temperature tests, a mathematical model for the post-rolling cooling control system has been developed. The experimental data is imported into MATLAB's System Identification Toolbox for system identification and parameter estimation. After preprocessing the data with the toolbox, the system model identification provides the corrected transfer function for the post-rolling cooling process, which is given by:

$$G(s) = \frac{30.16s}{s^2 + 2.224s + 0.3058} * e^{-0.8s} \tag{1}$$

2.2. Optimization of the Control System

In the steel production industry, feedback regulation is crucial. Currently, many steel mills use traditional PID control methods for adjustment. Although traditional PID control is straightforward to implement, it struggles with the nonlinearity and time-delay characteristics of the post-rolling cooling system. Moreover, when the parameters of the mathematical model change, traditional PID control cannot dynamically adjust its three parameters, making it difficult to set optimal values. This often leads to suboptimal control performance and fails to meet the precise control requirements for coiling temperature effectively.

With the advancement of intelligent control technologies, fuzzy control has gained attention as a promising alternative due to its robust performance and lack of dependence on precise mathematical models. However, the inherent fuzziness of the information can reduce system accuracy and affect dynamic performance. To address these challenges, this paper introduces a combined strategy that merges fuzzy control with PID control. By utilizing fuzzy reasoning for the adaptive tuning of PID parameters, this approach enables a more rapid and stable attainment of the desired coiling temperature.

Additionally, in the post-rolling cooling process, there are delays in heat conduction and temperature measurement response as the steel plate cools from high temperatures to the target temperature, resulting in system lag. To address this issue, the Smith predictor method is used to compensate for these delays. Combined with fuzzy PID control, this approach improves the system's response speed, enhances control accuracy, and reduces steady-state errors.

3. Control Principle of Fuzzy PID Based on Smith Predictor

3.1. PID Controller

The PID controller is a fundamental and extensively utilized component in discrete control systems. Its simplicity and ease of implementation make it the preferred choice for over 90% of control loops. The schematic diagram [11] is illustrated in the Figure 3.

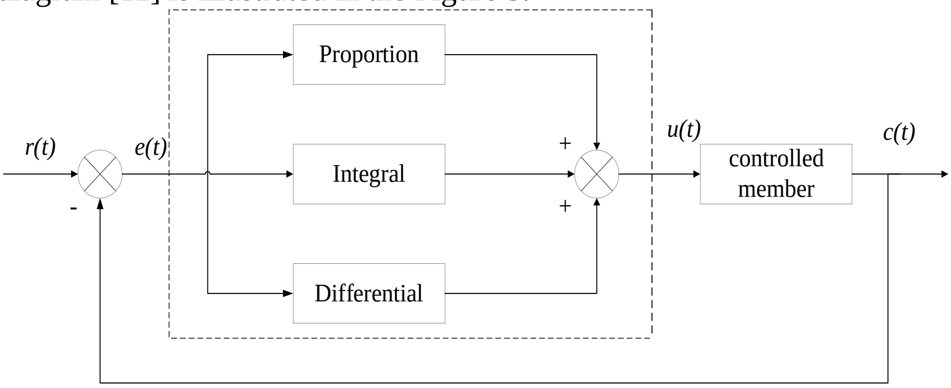

Figure 3: PID Control System Schematic Diagram.

In the diagram, r(t) denotes the reference setpoint, c(t) represents the actual output of the controlled system, e(t) indicates the deviation between the actual output and the reference setpoint, and u(t) is the control adjustment. Consequently, the system's error e(t) can be defined as follows:

$$e(t) = r(t) - c(t) \tag{2}$$

The PID controller is composed of three components: the Proportional unit (P), the Integral unit (I), and the Derivative unit (D). The control adjustment u(t) after the PID control operation is given by the following equation:

$$u(t) = Kp[e(t) + \frac{1}{Ti}\int e(t)dt + Td\frac{de(t)}{dt}] \tag{3}$$

In the equation, e(t) represents the error signal, Ti is the integral time constant, and Td is the derivative time constant. The parameters Ki =Kp/Ti and (Kd = Kp*Td, where Kp, Ki, and Kd are the proportional, integral, and derivative coefficients, respectively.

The performance of a PID algorithm's proportional, integral, and derivative components is determined by their respective parameters, making it essential to select the appropriate settings to ensure the system meets desired performance criteria. However, in traditional PID algorithms, the parameters Kp, Ki, and Kd are constant and cannot be dynamically adjusted. This limitation can lead to longer response times, increased overshoot, and difficulty in accurately controlling the steel plate's temperature during the post-rolling cooling process, especially when external disturbances are present.

3.2. Design of Fuzzy PID Controller

Fuzzy control is an algorithm based on fuzzy logic to describe and control processes, but it has limitations such as difficulty in eliminating steady-state errors and relatively low steady-state accuracy. To enhance the static performance of the fuzzy controller and the dynamic characteristics of the system, we integrate PID control with fuzzy logic algorithms.

To improve the dynamic performance of the post-rolling cooling control system for hot-rolled strip steel, this paper employs a two-dimensional fuzzy PID controller. In this configuration, the controller's input variables are the error e and its rate of change ec, while the output variables are the adjustments ΔKp,ΔKi and ΔKd for the PID parameters Kp, Ki, and Kd. During operation, the system continuously monitors the temperature error and its rate of change, allowing the fuzzy system to dynamically adjust the PID parameters Kp, Ki, and Kd in real time. This approach enables more precise and effective regulation of the control system's performance. The structure of the fuzzy PID controller is depicted in the figure 4[12-13].

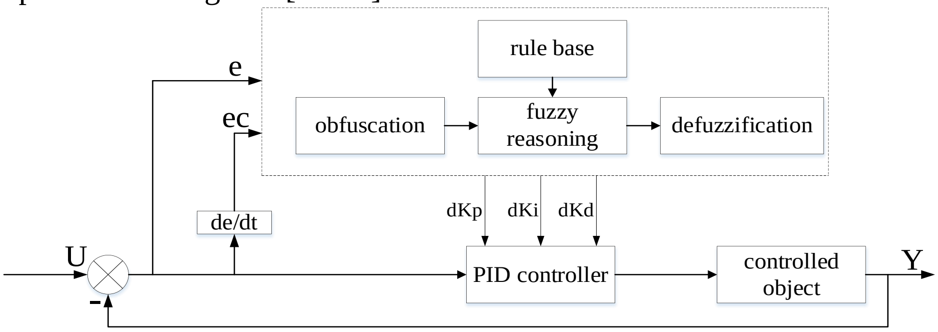

Figure 4: Principle of Fuzzy PID Controller.

The operation of the fuzzy controller, as illustrated in the figure 4, primarily involves three key components: the fuzzification of input variables, the formulation of fuzzy control rules, and the defuzzification of output variables.

3.2.1. Fuzification of Input Variables

The fuzzy subsets for e, ec, Kp, Ki, and Kd are defined as [NB, NM, NS, ZO, PS, PM, PB], representing Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, and Positive Big, respectively. Due to the complexity of the post-rolling cooling process and the variability in deviation ranges, different membership functions with varying resolutions are utilized. Gaussian membership functions are employed for the subsets NB and PB for e and ec, as they offer improved accuracy, stability, and robustness with their broad coverage. For the remaining subsets, triangular membership functions are chosen for ΔKp,ΔKi and ΔKd because of their high precision, simplicity, and computational efficiency. The membership functions for E and ΔKp are depicted in the Figure 5 and Figure 6.

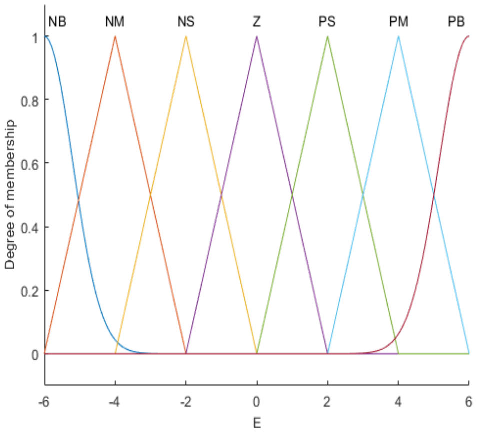

Figure 5: Membership Functions for E.

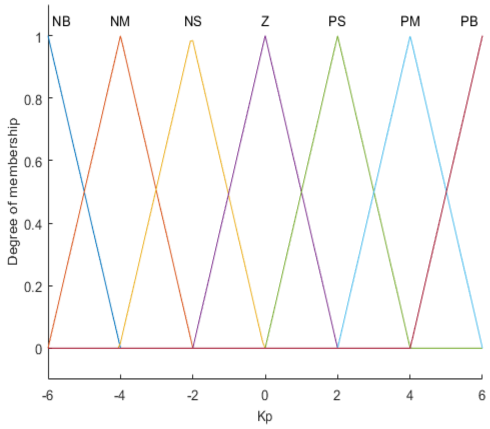

Figure 6: Membership Functions for Kp.

3.2.2. Establishing Fuzzy Control Rules

By designing the controller's output, both the static and dynamic characteristics of the system response can be optimized. The fuzzy control rules are crafted to minimize or correct system errors based on the output error E and the rate of change of the error de/dt. When E is substantial, the fuzzy inference should focus primarily on reducing or compensating for the error. Conversely, if E is small but the rate of change is significant, the fuzzy inference should prioritize maintaining system stability to avoid overshooting.

Through extensive study, experimentation, and the accumulation of expert experience in controlling the temperature of the post-rolling cooling system for hot-rolled strip steel, the fuzzy control rules for the three output variables ΔKp, ΔKi and ΔKd have been refined. (Table 1, Table 2 and Table 3)

Table 1: Fuzzy Rule Table for Proportional Coefficient Kp

E	EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	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

Table 2: Fuzzy Rule Table for Integral Coefficient Ki

E	EC						
	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	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 3: Fuzzy Rule Table for Derivative Coefficient Kd

E	EC						
	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	PS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

3.2.3. Defuzzification of Output Variables

Fuzzy inference produces a fuzzy set that must be defuzzified to generate a precise control signal for actuating the system. The Mamdani method is employed for the fuzzy logic inference, followed by the centroid method for defuzzifying the output. This approach ensures the stability of the system, as well as its dynamic response and steady-state performance. The calculation formula used for the centroid method is as follows:

$$u = \frac{\sum_{i}^{n} \mu(u_i) u_i}{\sum_{i}^{n} \mu(u_i)} \tag{4}$$

In this formula, u represents the precise value obtained after defuzzification of the output, u_i denotes the elements within the fuzzy set of the output domain, and $\mu(u_i)$ represents the membership degree of u_i.

Using the maximum membership principle, the fuzzy PID control parameters—namely proportional, integral, and derivative are adjusted to refine the output results, building upon the original PID parameters. The adjustment formula [14] is as follows:

$$\begin{cases} K'_p = K_p + \Delta K_p \\ K'_i = K_i + \Delta K_i \\ K'_d = K_d + \Delta K_d \end{cases} \tag{5}$$

In the formula, K'_p, K'_i, K'_d are the original values of the three control parameters; ΔK_p, ΔK_i, ΔK_d are the correction values for these control parameters.

3.3. Smith Predictor Control Algorithm

In industrial control systems, processes often experience significant delays that can cause considerable overshoot and slower response times. To significantly improve control performance and minimize instability in systems with such time delays, the Smith Predictor is commonly employed. By incorporating a compensator into the feedback loop, the Smith Predictor can anticipate the system's dynamic behavior under disturbances, thereby mitigating or even eliminating the effects of delays. This method significantly reduces overshoot and response time, improving both control performance and system stability. Additionally, it optimizes the adjustment process, making industrial control systems more efficient and reliable. The schematic diagram illustrating the principle of Smith prediction compensation control is presented in Figure 7[15].

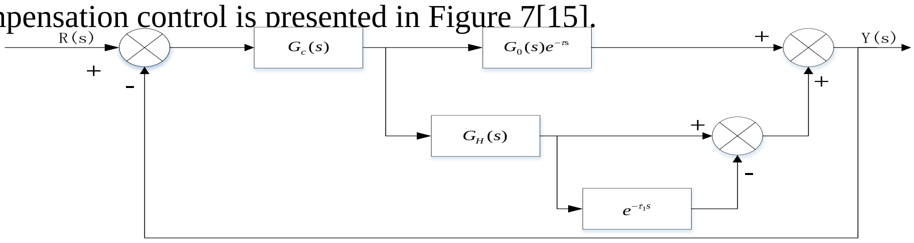

Figure 7: Smith Predictor Compensation Control Principle Structure Diagram.

In the diagram, $G_c(s)$ represents the transfer function of the system controller, $G_0(s)e^{-\tau s}$ indicates the transfer function of the controlled object, incorporating a delay time τ, and $G_H(s)$ is the transfer function of the Smith Predictor. R(s) and Y(s) correspond to the system's input and output, respectively. The closed-loop transfer function of the system is given by [16] as follows:

$$\varphi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)e^{-\tau s}}{1+G_c(s)G_H(s)(1-e^{-\tau_h s})+G_c(s)G_0(s)e^{-\tau s}} \tag{6}$$

In the equation, τ_1 represents the delay function within the Smith Predictor.

In an ideal scenario, if the model of the controlled object is known, you can set $G_H(s) = G_0(s)$, $\tau_1 = \tau$. Consequently, the closed-loop transfer function of the system is expressed as follows:

$$\varphi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)e^{-\tau s}}{1+G_c(s)G_0(s)} \tag{7}$$

The closed-loop transfer function shows that the characteristic equation of the system no longer includes the pure delay term. This demonstrates that, relative to the original system, the influence of pure delay on the stability of the closed-loop system has been effectively removed.

3.4. Smith-Fuzzy PID Control

For complex control systems like the post-rolling cooling control system, which exhibit nonlinearity, time-varying characteristics, and time delays, a simple PID controller may not achieve satisfactory results. To enhance control accuracy, the Smith Predictor is combined with a Fuzzy PID controller, creating the Smith-Fuzzy PID control algorithm. This approach includes two key elements: first, the Smith Predictor, which mitigates the effects of time delays on temperature control precision during the cooling process; and second, the Fuzzy Controller, which adaptively adjusts the PID parameters to account for temperature fluctuations in the cooling system. The principle diagram of the Smith-Fuzzy PID controller is depicted in the figure 8.

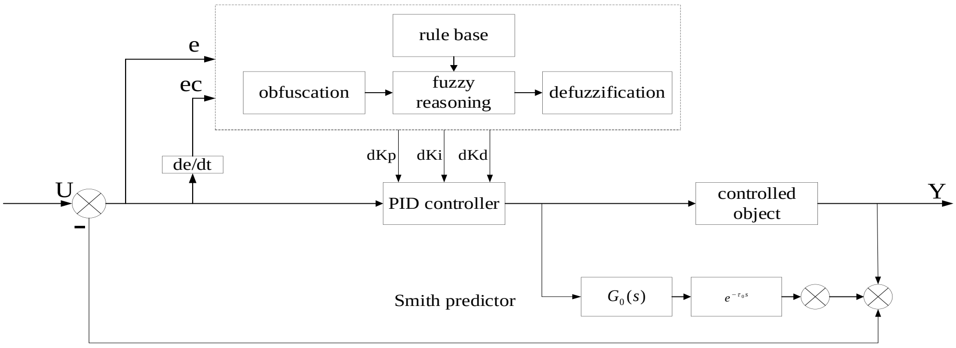

Figure 8: Smith-Fuzzy PID Controller Principle Diagram.

4. System Simulation and Results Analysis

To assess the effectiveness of the developed temperature control system for post-rolling cooling of hot-rolled strip steel, simulation experiments were carried out using the step response method to establish the system model. Based on theoretical analysis, simulation models for traditional PID control, fuzzy PID control, and Smith-Fuzzy PID control were created in the MATLAB/Simulink environment. These models were then compared and analyzed to evaluate their control performance.

A step signal was applied to the control system, with the initial PID controller parameters configured as Kp = 0.7, Ki = 0.2, and Kd = 0.05, reflecting the specific operational conditions of the hot-rolled strip steel post-rolling cooling system. The simulation models for both conventional PID control and fuzzy PID control are shown in the Figure 9, Figure 10, and Figure 11.

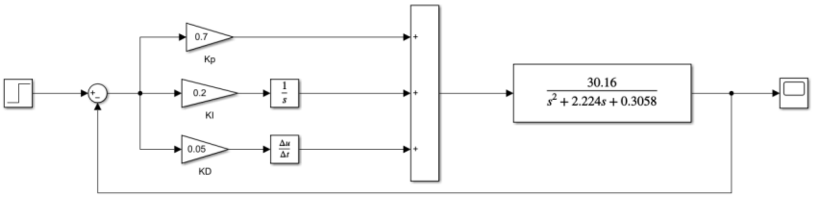

Figure 9: Conventional PID Control Simulation Diagram.

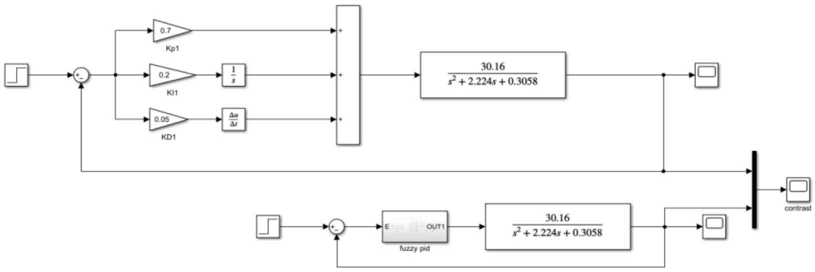

Figure 10: Fuzzy PID Control Simulation Diagram(1).

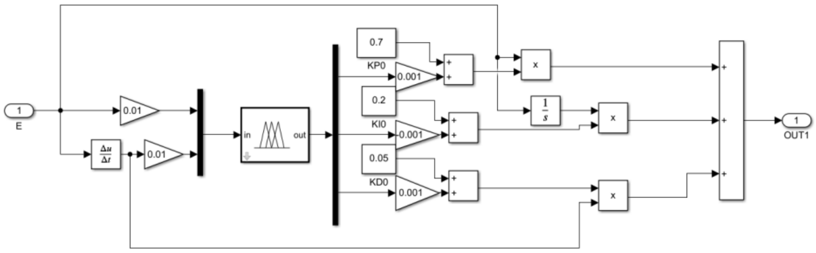

Figure 11: Fuzzy PID Control Simulation Diagram(2).

Below is a comparison of the simulation results for the two types of controllers, as shown in the figure 12.

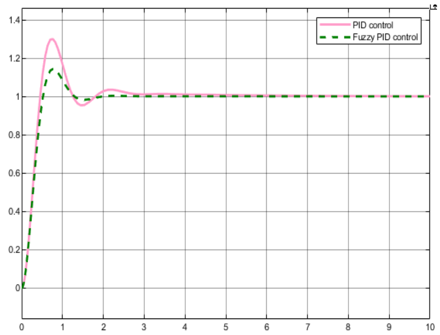

Figure 12: Simulation Comparison Chart.

The simulation results indicate that both the traditional PID controller and the fuzzy PID controller exhibit significant overshoot, prolonged rise and settling times, and some steady-state error, resulting in suboptimal control performance.

To address these issues, this study introduces the Smith prediction compensation control algorithm to refine the fuzzy control approach. By designing a Smith prediction compensator and integrating it into the fuzzy control scheme, an enhanced control strategy is developed. The block diagram of the simulation model for this improved control approach is shown in the figure 13.

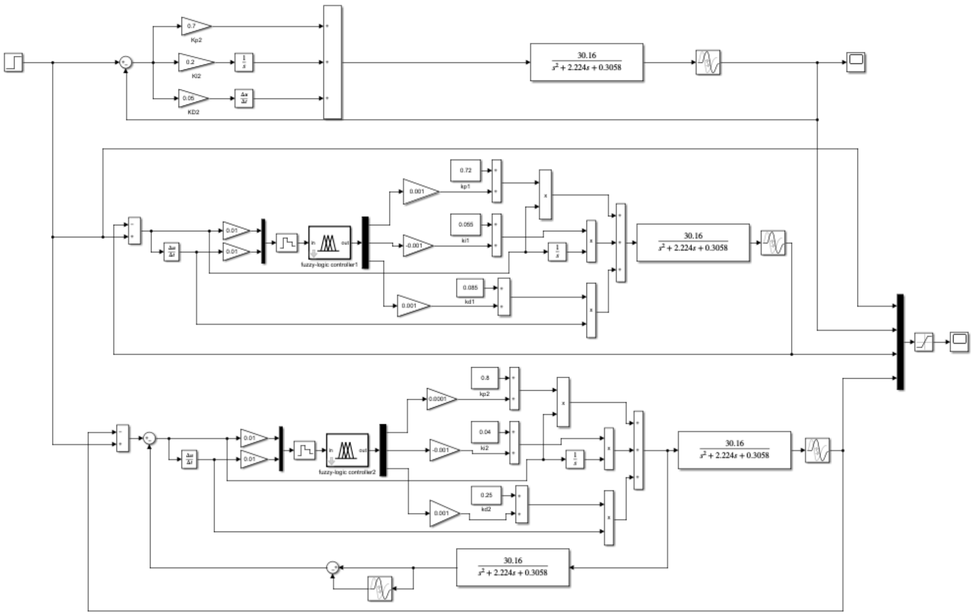

Figure 13: Smith-Fuzzy PID Temperature Control System Model.

The simulation results are shown in the figure 14.

Analysis of the simulation results shows that the Smith-Fuzzy PID controller surpasses the other two control algorithms in several key areas. It achieves a faster temperature rise, exhibits smaller overshoot, and reaches a stable temperature more quickly. This significantly improves the performance of the post-rolling cooling system, enhances its adjustment capabilities and disturbance resistance, and effectively mitigates the impact of pure delay. The system achieves the desired steady-state characteristics with this control method.

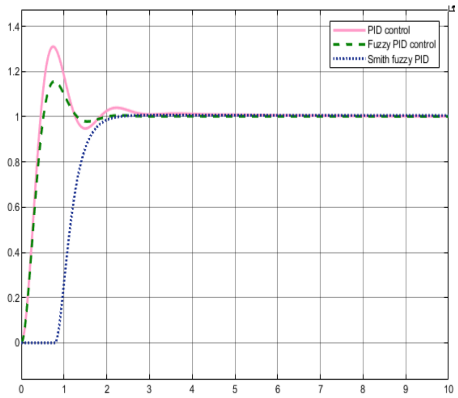

Figure 14: Comparison of simulation results for the three controllers.

5. Conclusion

The control and cooling technology for hot-rolled strip steel is crucial for the quality and performance of finished steel products, with coiling temperature being a key control parameter. The precision of this parameter is crucial for the stability of the post-rolling cooling system. To tackle the time-varying and time-delay issues inherent in the hot-rolled strip steel cooling process, this paper proposes a PID control strategy that combines Smith prediction control with fuzzy control theory.

To validate this approach, simulation models of three types of controllers were developed and compared. The simulation results indicate that incorporating the Smith-Fuzzy PID controller markedly enhances control performance. This approach not only decreases overshoot and adjustment time but also improves response speed and stability.

By incorporating the Smith fuzzy PID controller, precise temperature regulation of the post-rolling cooling system is achieved, significantly addressing system lag issues. This method proves to be highly effective in control systems with significant lag and is crucial for advancing the intelligent and rapid development of temperature regulation in industrial control.

Acknowledgments

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