# *EXPLORING THE OPTIMAL DESIGN OF COMPUTER CONTROL SYSTEM FOR HEATING BOILERS IN POWER PLANTS*

***Jia Mao* [1], *Qi Sun* [1], *Ju Wang* [2*]**

1.School of Transportation, Jilin University,Changchun City,Jilin Province,China

2. College of New Energy and Environment, ,Changchun City,Jilin Province,China

[*]Corresponding author: Ju Wang; E-mail: maojia_jlu@163.com

*Abstract: Objective: For stable and efficient control of the heating boilers in power plants, an improved Smith-fuzzy PID algorithm is used to optimize the computer control system for heating boilers. Methods: Under the computer control system, the pressure, exhaust gas temperature, water temperature, safety, and energy consumption of heating boilers are explored, thereby determining the optimization effect of the computer control system. Results: The improved Smith-fuzzy PID algorithm has the optimal control effect on water temperature and pressure of the heating boilers, with the highest balance and stability. In comparison, the fluctuations in temperature control curves under Smith-PID and PID algorithms are large. Compared with the exhaust gas temperature of the other two algorithm systems, the exhaust gas temperature of the improved Smith-fuzzy PID algorithm-based computer system is reduced by 40°C, which decreases the consumption of coal resources. Conclusion: The improved Smith-fuzzy PID algorithm-based heating boiler computer control system has the most prominent effects on water temperature, pressure, and exhaust gas temperature. The designed system is accurate and reliable, satisfying the actual design requirements of computer control systems for heating boilers.*

Key words: *boilers; temperature; pressure; algorithm; exhaust gas*

## 1. Introduction

With the development of science and the progress of society, people are becoming more dependent on energy. Regardless of personal life or the development of the country and society, the status of resources has become increasingly prominent [1]. However, as resource reserves become less, saving and efficient use of resources have become a critical concern to society and the country. Especially in China, with a large population, it is even more dependent on resources [2]. Therefore, more in-depth research should be conducted on the efficient use of resources and energy saving. The technology of efficient energy use has significantly changed the function and role of resources. It is an important way to obtain the hidden value of sustainable energy development [3]. At the current stage, the utilization efficiency of China's fossil energy is extremely low, causing tremendous energy loss and waste and bringing about severe pollution and safety issues. Ultimately, it leads to a continuous increase in energy costs [4]. Realizing energy efficiency and conservation is difficult and challenging, in which the professional talents and technologies are required, and the investment in research and development is large. If the effect of the control system is unreasonable, not only will it be unable to achieve savings but it will also bring huge economic losses, as well as difficulties in the planning of daily works [5]. The control effect of the current energy control system on energy loss is unsatisfactory. The main reason is that the control ability is relatively poor, and the key parameters cannot be stable and reliable [6]. Such a situation has seriously increased the loss and waste of energy. Without a comprehensive and in-depth study of all factors of energy loss, effective control cannot be achieved. Therefore, a comprehensive and in-depth understanding is a core link for optimizing the current energy control system. If the efficiency and loss of energy control cannot be guaranteed [7], problems such as energy waste, energy loss, and low utilization rate will continuously exist, and the resulting losses are difficult to estimate [8,9].

Therefore, this study proposes to use an improved Smith-fuzzy PID algorithm to optimize the computer control system for heating boilers. By optimizing the current heating boiler system, the control efficiency and safety factors of the system are improved, the energy consumption is reduced, and the efficient reuse of energy is achieved. The contribution of this study lies in the utilization of an improved Smith-fuzzy PID algorithm to study and overcome the practical difficulties of low efficiency of heating boiler systems during applications, thereby effectively solving the difficulties of energy control caused by safety bugs and energy waste. Controlling and saving energy has significant values in both the fields of daily life and science and technology.

## 2. Methodology

### 2.1. The heating boiler system in power plants

According to the composition of the system, the heating boiler system of the power plant is mainly divided into the supplementary pump control link, the circulation pump control link, the data acquisition link, and the drain pump control link [10]. The overall framework of the heating boiler combustion control is shown in Fig. 1. These four links are interconnected to form an organic ecosystem. Among them, the data collection link is a critical step, which is mainly composed of two stations, i.e., the slave station and the master station. The two stations share the same switching value; therefore, they can achieve the effect of redundancy. The biggest advantage of this design is in the aspect of safety performance [11]. If the slave station or the master station stops working due to failure or other reasons, it will not cause complete paralysis of the system, which will greatly improve the security of the system. The core work of the master station is mainly to collect the relevant parameters in the system operating procedures and control the key equipment and valves on the site. A monitoring system is installed in the master station, which can realize real-time monitoring and control of each link and step [12]. The purpose of the slave station is to collect and process the temperature parameters in the system control process. The slave station and the master station rely on the bus for effective communication. There is no monitoring facility installed in the slave station. Therefore, the slave station needs to transmit the collected temperature data to the master station for effective monitoring through the bus. The circulation pump link of the heating boiler system is controlled by a chopper. The drain pump and make-up pump link mainly rely on the speed transmission for adjustment and control [13].

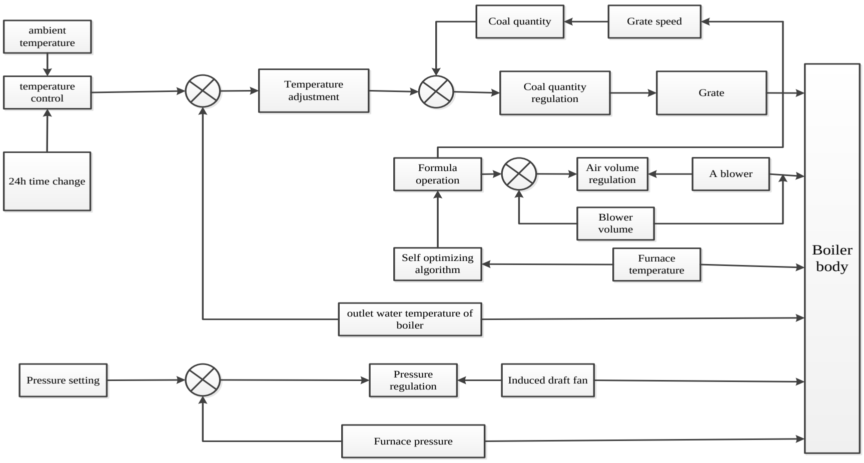

Figure 1 The combustion control of heating boilers

## 2.2. Techniques of heating boilers

The major processes of this system are shown below. The first step is to use a frequency converter to start the normal operation of the water supplement pump to achieve a full-scale water supplement operation of the pipeline network [14]. When the pressure value of the pipe network meets the set value, the inverter will start the circulating pump to work and realize the water supplement operation for the heat exchanger. When the amount of water in the heat exchanger reaches the set required position, the steam valve is opened immediately, and the heat engine is used to realize the steam injection operation of the heat exchanger [15]. After the heat exchangers interact with each other, heating and transportation for the residents can be realized; after reheat exchange, the remaining condensate water is returned to the water tank through the pipe network. In the next step, the inverter is used to start the drain pump, and the condensate water in the water tank is sent back to the boiler for reuse through the pipe network, avoiding waste. If the temperature of the return water cannot reach the temperature of the water supply, the speed of the circulating water pump needs to be accelerated to increase the amount of circulating water. At the same time, it is also necessary to increase the amount of steam to increase the temperature of the water supply, thereby satisfying the requirements for the water temperature in the pipeline. The major control objects of heating boilers are shown in Fig. 2.

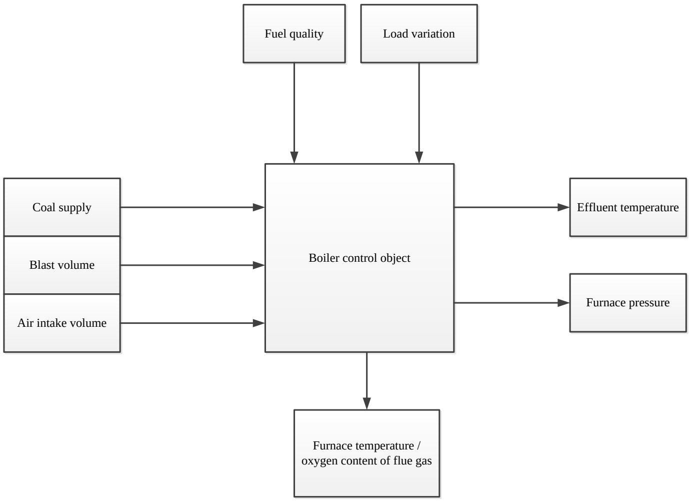

Figure 2 Control objects of heating boilers

### 2.3. Major tasks of heating boilers

The heating boiler is a complex device, and its water supply process is shown in Fig. 3. Its main task is to ensure that the boiler outlet temperature is constant under the premise of safe operation of the boiler, to meet the heating requirements of users, to improve the boiler combustion efficiency, and to save the costs. Its main control requirements are as follows.

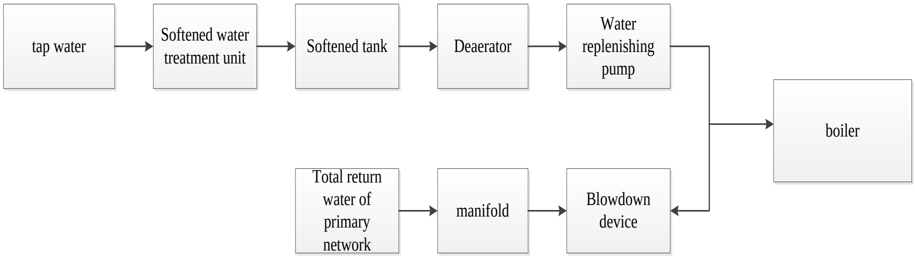

**Figure 3 The processing flow of water supply**

Ensuring the stability of boiler water supply temperature: In heating boilers, the temperature is an essential parameter. If the temperature of the water cannot meet the heating demand, or the temperature is in an unstable state, it cannot meet the normal heating requirements. The most important thing is that in winter, the temperature changes are relatively large and repeated. Therefore, it is necessary to continuously adjust and control the temperature of the water supply to meet the real-time demand without causing wastes. This is the requirement for temperature control of the heating boilers.

Ensuring the highest combustion efficiency of the boiler system: The combustion efficiency is the lifeblood for heating companies. Low efficiency will waste huge resources and bring a very large economic burden. Therefore, combustion efficiency is an important criterion for measuring boiler quality. If the combustion efficiency cannot be guaranteed, the boiler will not work continuously and stably. The heating system will automatically search for the optimal wind-to-coal ratio according to the changes to adjust the blower volume accordingly so that the coal in the boiler can be fully burnt, realizing the optimal combustion efficiency. The combustion efficiency curve is shown in Fig. 4.

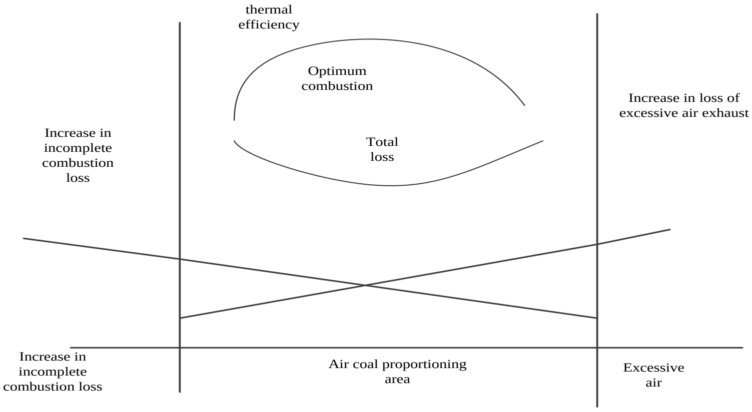

**Figure 4 The combustion efficiency curve**

Maintaining pressure in the furnace: Safety is a prerequisite for the normal operation of the boiler. Furnace negative pressure control means that by adjusting the rotation speed of the boiler induced-draft fan, the furnace pressure is always maintained in a negative state to meet the working conditions required by the boiler, avoiding the explosion of the boiler hearth due to sparks and ensuring the safety of operators, as well as preventing flue gas leaks due to the tightness of the combustion process.

### 2.4. Model construction of control system for heating boilers

A micro-element with a length of dy is taken in the tube, and its cross-sectional area is F. According to the conservation of mass, the micro-element in per unit time has:

$$D - \left( D + \frac{\partial D}{\partial y} dy \right) = \frac{dM}{dt} \tag{1}$$

Where M is the mass of the micro-element medium, and D is the flow rate of the medium. Thermal power plants mostly use the thermal method to quantitatively evaluate their thermal economy. Thermal cycle efficiency is one of the important thermal economic indicators, which can be calculated according to the following equation:

$$\eta = 1 - \frac{\Delta Q_c}{Q_0} \tag{2}$$

Where $\Delta Q_c$ is the heat loss from the cold source, which can be used to characterize the degree of thermal power conversion of the new steam. To perform a heat transfer calculation on the heating surface of a boiler, it is necessary to know how to calculate the enthalpy of air and flue gas. The calculation equation of the actual air enthalpy is:

$$h_k = \beta h_k^o = \beta V^0 (c\theta)_k \tag{3}$$

The actual enthalpy of the flue gas is calculated as:

$$h_y = h_y^o + (\alpha - 1) h_k^o + h_{fh} \tag{4}$$

Where $B_j$ is the calculated fuel value. In the heating boilers of coal-fired power plants, the value should be the calculated fuel consumption that considers the heat loss of the incomplete solid fuel, and the corresponding calculation equation is:

$$B = B_j \left( 1 - \frac{q_4}{100} \right) \tag{5}$$

$$\begin{gathered} M \left( \mu + \frac{w^2}{2} + gh \right) = F\rho dy \left( \mu + \frac{w^2}{2} + gh \right)_0 \\ N = D \left( \mu + \frac{w^2}{2} + gh \right) \end{gathered} \tag{6}$$

If the volume of the micro-element is small, the subscript “0” can be removed. Since the system has no mechanical work output and no fixed expansion work, according to the first law of thermodynamics:

$$Q_2 dy - \left[ \frac{\partial N}{\partial y} dy + \frac{\partial (Fpw)}{\partial y} dy \right] = \frac{\partial}{\partial t} \left[ F\rho dy \left( \mu + \frac{w^2}{2} + gh \right) \right] \tag{7}$$

The heat release $Q_2$ of the metal pipe wall per unit length to the medium in the pipe can be expressed as:

$$Q_2 = \alpha_2 \pi d_2 \left( T_j - T \right) = \alpha_1 \alpha_2 \left( T_j - T \right) \tag{8}$$

Heat balance equation of metal on the wall of the heated pipe:

$$Q_1 - Q_2 = m_j c_j \frac{\partial T_j}{\partial t} \tag{9}$$

Where $m_j$ is the metal mass of the heating pipe per unit length, and $c_j$ is the specific heat capacity of the metal of the heating pipe. When the flue gas flows along the length of the pipe, if the change in specific heat is ignored, the energy equation can be listed as follows:

$$Q_1 = -c_y G_y \frac{\partial T_y}{\partial y} \tag{10}$$

The heat released from the flue gas to the pipe wall depends on the heat transfer properties. The heat release equation of the flue gas from the convection heat transfer area to the pipe wall is:

$$Q_1 = Q_{1d} + Q_{1j} = \alpha_{1d} \pi d_1 \left(T_y - T_1\right) + \alpha_{1f} \pi d_1 \left(T_y - T_1\right) \tag{11}$$

To easily establish the transfer function between the single-phase heating tube outlet enthalpy and the input variables of the heat transfer system, the basic equation of the boiler medium are linearized. It is assumed that the combustion process of the boiler only changes in a small amount near a certain steady-state operating condition ratio,

$$Q_0 = \alpha_0 \partial_2 \left(T_j - T\right)_0 = \frac{D_0 \left(H_{20} - H_{10}\right)}{l} = D_0 c_p \frac{T_{20} - T_{10}}{l} \tag{12}$$

Linearizing the heat balance equation of the tube wall of the heated pipe and expressing it with relative quantities can obtain:

$$q_1 - q_2 = T_m \frac{\partial \theta_j}{\partial t} \tag{13}$$

Linearizing the relation between the heat release equation and the heat release coefficient of the heated medium to the medium water in the pipe and expressing it with relative quantities can obtain:

$$\begin{gathered} q_2 = nd + \theta_j - \alpha_d \eta \\ \alpha_d = \frac{T_{20} - T_{10}}{\left(T_j - T\right)_0} = \frac{\alpha_{20} A_2}{D_0 c_P} \end{gathered} \tag{14}$$

Linearizing the momentum equation and energy equation of the medium water in the heated pipe when the medium water flows in a steady state can obtain:

$$q_2 = l \frac{\eta}{y} + d + t_0 \frac{\eta}{t} - \frac{FP_0}{Q_0} \frac{dp}{dt} \tag{15}$$

In this study, the equivalent enthalpy drop method is used to calculate the thermodynamic energy saving of the flue gas waste heat utilization system. According to the equivalent enthalpy drop theory, the equivalent enthalpy drop $H_j$ of each stage of extraction can be summarized as the following equation:

$$H_f = \left(h_j - h_c\right) - \sum_{j=1}^{r=m} \frac{A_r}{q_r} H_r \tag{16}$$

After calculating the equivalent enthalpy drop $H_f$ of each stage of steam extraction, the corresponding extraction efficiency is calculated based on the ratio of equivalent enthalpy drop to the added heat:

$$\eta_j = \frac{H_j}{q_j} \tag{17}$$

For reheating units, the boiler can be regarded as a collective heater; therefore the gross equivalent heat drop of the new steam is:

$$H_{gr} = h_0 + q_{rh} - h_c - \sum_{r=1}^{8} \tau_r \eta_r \tag{18}$$

It is assumed that the specific heat capacity v and y have a linear relationship under steady-state conditions; therefore:

$$v\left(y, 0\right) = v_{10} + \left(v_{20} - v_{10}\right) \frac{y}{l} \tag{19}$$

A new variable dt is introduced, where w is the flow rate. Considering D10=D20 at steady state, it can be obtained that:

$$\omega = \omega\left(y, 0\right) = \omega_{10} + \left(\omega_{20} - \omega_{10}\right)\frac{y}{l} \tag{20}$$

At this time, the flow time $t_0$ can be expressed as:

$$t_0 = \int_0^1 dt_y = \int_0^1 \frac{dy}{\omega_{10} + \left(\omega_{20} - \omega_{10}\right)\frac{y}{l}} = \frac{l}{\omega_{20} - \omega_{10}} \ln \frac{v_{20}}{v_{10}} \approx \frac{l}{v} \tag{21}$$

The continuity equation of the medium, the thermal equilibrium equation, and the equation of heat release from the tube wall metal to the medium are combined as follows:

$$D_1 - D_2 = V\frac{d\rho_2}{dt} \tag{22}$$

$$Q_0 + D_1H_1 - D_2H_2 = V\frac{d}{dt}\left(\rho_2 H_2\right) \tag{23}$$

$$Q_2 = K_2 D_2^2 \left(T_j - T_z\right) \tag{24}$$

By linearizing the above types, the transfer function of the outlet temperature and the heat of the medium outside the tube can be obtained:

$$W_T\left(s\right) = \frac{\Delta T_2}{\Delta Q_1} = \frac{V\frac{Q_0}{T_d}\rho_{2\varphi}c_p}{\frac{Q_0}{T_d}D_0c_p + \left[\left(\frac{Q_0}{T_d} + D_0c_y\right)M_jc_j + V\frac{Q_0}{T_d}\rho_{2\varphi}c_p\right]s} \tag{25}$$

## 2.5. Operation steps of the boiler control system

System control operation steps: (1) After the system startup detection and parameter setting are initialized, the boiler water level is checked. If the water level is low or high, an emergency alarm will be displayed and it will automatically stop immediately. If the water level is at low I, an alarm will be displayed and the water injection pump will be automatically started to replenish the boiler. If the water level is higher than the low I position, the boiler operation is started normally. (2) The boiler is ignited, and the air pump is turned on to start heating the boiler. If the detected water level is at the high I position, an alarm is displayed and the water discharge valve is automatically opened to discharge water; if the water level is lower than the high I position, the boiler is heated normally. (3) When the water injection reaches the liquid level set by the boiler, the user valve is opened, and the steam is output to the users. The wind-to-coal ratio control flowchart is shown in Fig. 5. At the same time, the neural network predictive control in PLC is used to ensure that the boiler drum water level fluctuates slightly within a certain stable value range. When the boiler drum water level is in a relatively stable range, the boiler combustion control system program starts to run.

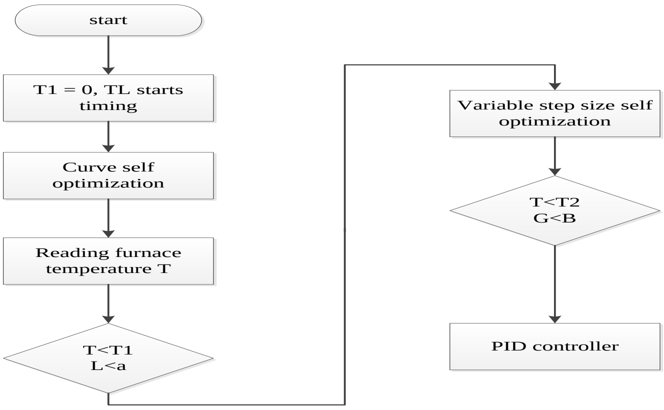

**Figure 5 Flowchart of wind-to-coal ratio step control**

Steps for boiler combustion control system program operations: The boiler combustion control system program is started. The primary and secondary water supply reference temperature of the system is read. The primary and secondary water supply temperature is collected. The collected temperature is compared with the primary and secondary water supply reference temperature. If T2<T1, the system automatically operates raising the grate speed, raising the fan speed, and raising the induced fan speed; otherwise, it automatically performs the operations of lowering the grate speed, lowering the fan speed, and lowering the fan speed. Combustion control is mainly to control the amount of fuel, supply air and induced air of the boiler, thereby satisfying the heat required by the boiler system and the external requirements of the boiler output steam load, as well as ensuring the safety and economy of the boiler operation. When controlling the boiler combustion, the primary water supply pressure parameters are collected. If the water supply pressure parameter exceeds the standard, an alarm is displayed. At the same time, the speed of the circulating water pump is increased to accelerate heat transfer, thereby reducing the pressure. If the water supply pressure parameter is normal, the combustion control system is executed cyclically.

## 3. Results and discussion

The study of the temperature control curves of the improved Smith-fuzzy PID algorithm, Smith-PID algorithm, and PID algorithm is shown in Fig. 6. As shown in Fig. 6, among the algorithms used in this study, the improved Smith-fuzzy PID algorithm has the best optimization effect on the computer control system for the heating boilers. During the time of the experiment, the temperature fluctuation is very small, which can meet the control requirements of the actual heating boiler computer control system for the water temperature. In comparison, the temperature control curve fluctuations of the Smith-PID and PID algorithms are relatively obvious, with temperature fluctuations of about 8 degrees, and their practical application effects are relatively poor. Therefore, the power plant heating boiler computer control system based on the improved Smith-fuzzy PID algorithm has a very good temperature control effect on the boiler and has very high adaptability in practical application. The obtained temperature data is trustworthy. This can verify the reliability of the system designed in this study.

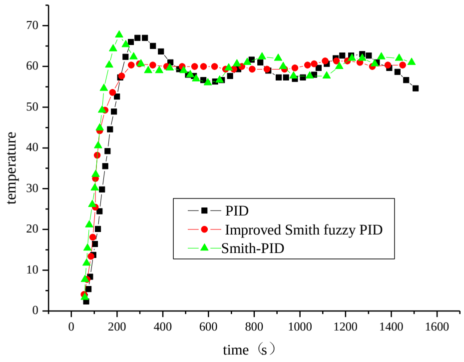

**Figure 6 The temperature control curves of improved Smith-fuzzy PID algorithm, Smith-PID algorithm, and PID algorithm**

The comparison of the pressure control curves among the improved Smith-fuzzy PID algorithm, the Smith-PID algorithm, and the PID algorithm is shown in Fig. 7. As shown in the three sets of pressure operating curves in Fig. 7, the improved Smith-fuzzy PID algorithm-based computer control system for heating boilers used in this study is the most powerful and effective in controlling the pressure of the heating boilers in the power plant. During the time of the experiment, the pressure fluctuation is relatively small, which can fully meet the needs for the balance of the actual heating boiler pressure. However, the pressure control curves of Smith-PID and PID algorithms fluctuate greatly with obvious pressure fluctuations, which cannot meet the actual demand. Therefore, the computer control system of power plant heating boilers based on the improved Smith-fuzzy PID algorithm can meet the actual needs for the pressure control effect of the boilers, and its application has very high adaptability, which can verify the efficiency of the system designed in this study.

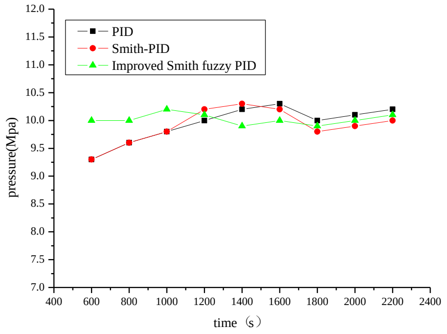

**Figure 7 The pressure control curves of improved Smith-fuzzy PID algorithm, Smith-PID algorithm, and PID algorithm**

The comparison of the exhaust gas temperature control curves among the improved Smith-fuzzy PID algorithm, the Smith-PID algorithm, and the PID algorithm is shown in Fig. 8. As shown in the three sets of exhaust gas temperature control curves in Fig. 8, the heating boiler computer control system based on the improved Smith-fuzzy PID algorithm has the most obvious ability to reduce the exhaust gas temperature of the heating boiler in the power plant, reducing the heat of the exhaust gas temperature, thereby decreasing the ineffective consumption of energy, cuts down the wastes of resources, and improves the efficiency of boiler heating. During the time of the experiment conducted in this study, the exhaust gas temperature of the proposed computer control system based on the improved Smith-fuzzy PID algorithm is maintained at about 130 degrees, which is much lower than the exhaust gas temperature of 170 and 180 degrees under the other two algorithms. Therefore, the computer control system for power plant heating boilers based on the improved Smith-fuzzy PID algorithm has the optimal effect on the boiler exhaust gas temperature control, and its application has very high adaptability.

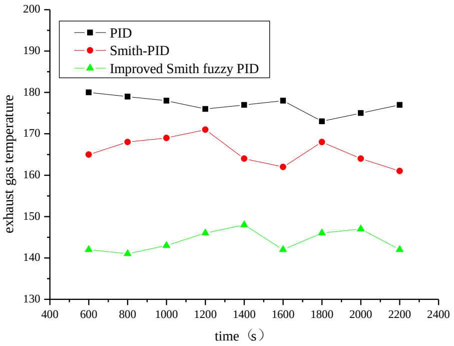

**Figure 8 The exhaust gas temperature control curves of improved Smith-fuzzy PID algorithm, Smith-PID algorithm, and PID algorithm**

## 4. Conclusions

In this study, an improved Smith-fuzzy PID algorithm is used to optimize the computer control system for the heating boilers. This study mainly focuses on the boiler pressure, boiler exhaust gas temperature, boiler water temperature, boiler safety, and boiler energy consumption, thereby determining the optimization effect of the computer control system. The research results show that compared with Smith-PID and PID algorithms, the improved Smith-fuzzy PID algorithm has the optimal control effect on the water temperature and pressure of the boilers. Meanwhile, its balance and stability are the highest. Compared with the exhaust gas temperature of the other two algorithm systems, the exhaust gas temperature of the improved Smith-fuzzy PID algorithm-based computer system is reduced by 40°C, which saves lots of resources and decreases the consumption of coal resources. The research in this study is also limited. For example, since the actual boiler operating conditions are complex and unstable, the analysis and calculation of some factors ignore the interference factors and the results obtained are less convincing. In addition, some aspects of the data requirements are very high, but the experiment in this study can only obtain a data range instead of accurate figures. Therefore, the subsequent research will be more in-depth, meticulously, and comprehensively to reduce the interference caused by other factors. The research results of this study have important reference values for future research.

## References

[1] Dolatabadi, A., *et al.*, Optimal stochastic design of wind integrated energy hub, *IEEE Transactions on Industrial Informatics*, *13* (2017), 62, pp. 379-2388.

[2] Rodríguez, L. R., *et al.*, Analysis of the economic feasibility and reduction of a building’s energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems, *Applied Energy*, *165* (2016), 6, pp. 828-838.

[3] Shaofei Wu. Study and evaluation of clustering algorithm for solubility and thermodynamic data of glycerol derivatives, Thermal Science, 23(2019), 5, pp.2867-2875.

[4] Tezer, T., *et al.*, Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems, *Renewable and Sustainable Energy Reviews*, *73* (2017), 9, pp. 840-853.

[5] Maroufmashat, A., *et al.*, Multi-objective optimization for design and operation of distributed energy systems through the multi-energy hub network approach, *Industrial & Engineering Chemistry Research*, *55* (2016), 33, pp. 8950-8966.

[6] Thomas, D., *et al.*, Optimal design and techno-economic analysis of an autonomous small

isolated microgrid aiming at high RES penetration, *Energy, 116* (2016), 11, pp. 364-379.

[7] Wang, H., *et al.*, Optimal design and operation of CHPs and energy hub with multi objectives for a local energy system, *Energy Procedia*, *142* (2017), 13, pp. 1615-1621.

[8] Li, Y., *et al.*, Optimal design of PCM thermal storage tank and its application for winter available open-air swimming pool. *Applied Energy, 209* (2018), 11, pp. 224-235.

[9] Calise, F., *et al.*, Optimal operating strategies of combined cooling, heating and power systems: A case study for an engine manufacturing facility, *Energy Conversion and Management, 149* (2017), 12, pp. 1066-1084.

[10] Evins, R., A bi-level design and operation optimization process applied to an energy centre, *Journal of Building Performance Simulation, 9* (2016), 3, pp. 255-271.

[11] Shaofei Wu,A Traffic Motion Object Extraction Algorithm,International Journal of Bifurcation and Chaos, 25(2015),14,Article Number 1540039

[12] Ubando, A. T., *et al.*, Fuzzy mixed integer non-linear programming model for the design of an algae-based eco-industrial park with prospective selection of support tenants under product price variability, *Journal of cleaner production, 136* (2016), 15, pp. 183-196.

[13] Tzortzis, G. J., Frangopoulos, C. A., Dynamic optimization of synthesis, design and operation of marine energy systems, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *233* (2019), 2, pp. 454-473.

[14] Vesterlund, M., Toffolo, A., Design optimization of a district heating network expansion, a case study for the town of Kiruna, *Applied Sciences, 7* (2017), 5, pp. 488.

[15] Picard, D., Helsen, L., Economic optimal HVAC design for hybrid GEOTABS buildings and $CO_2$ emissions analysis, *Energies, 11* (2018), 2, pp. 314.