Open Access Library Journal
2022, Volume 9, e7586
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Design of Medium-Pressure Industrial Natural Circulation Boiler Control System Based on PCS7

Xin Ai

Chengdu University of Technology, Chengdu, China
Email: 1430249131@qq.com

How to cite this paper: Ai, X. (2022) Design of Medium-Pressure Industrial Natural Circulation Boiler Control System Based on PCS7. *Open Access Library Journal*, **9**: e7586.
https://doi.org/10.4236/oalib.1107586

Received: June 28, 2021
Accepted: March 14, 2022
Published: March 17, 2022

Abstract

Medium pressure natural circulation boiler is a common heat exchange pressure device in industry. The object has complex characteristics such as MIMO, strong coupling and uncertainty. It is difficult to achieve ideal control effect by using traditional controller to deal with the change of working conditions. In this study, SIMATIC PCS7 is used as the controller, CFC and SFC are used to complete different control loop configurations, so as to realize the control of superheated steam flow, superheated steam temperature, flue gas oxygen content, drum water level and furnace negative pressure, so as to make the system run smoothly. The system test shows that the designed control system can maintain a good and stable operation state under normal conditions. At the same time, it can also ensure the stable operation under certain load change requirements, and has a certain anti-interference ability.

Subject Areas

Mechanical Engineering

Keywords

Control System, PID Algorithm, The SMPT-1000 Experimental Device, PCS7

1. Introduction

Boilers play a vital role in my country's industrial production and residents' lives. According to relevant data [1], the number of major industrial boilers and motive power manufacturers in my country has reached more than 1200 in 2012, with total industry assets more than 412.2 billion yuan, and on this basis, it is showing a trend of rapid growth. Therefore, as my country increases its efforts to promote the development of the manufacturing industry and the "Made in China 2025" proposal, more and more boilers will be put into use every year.

As a complex and long-term energy conversion equipment operating under high temperature and high pressure environment, the boiler is widely used in all walks of life, so it has extremely high requirements for its safety and efficiency. In order to meet its safety and efficiency requirements, boilers have different classification methods according to different standards. According to the difference in the outlet pressure of the boiler heating steam, we can classify the boiler into different types of boilers such as low pressure, medium pressure, high pressure and ultra high pressure; and according to the different ways of steam-water circulation inside the boiler, it can be divided into: forced circulation boiler and natural circulating boiler. Among them, the medium-pressure boiler is a boiler with a superheated steam pressure of 2.94 - 4.90 MPa. Most of them use pulverized coal or fuel oil, solid slag discharge, and the steam-water circulation method is natural circulation. Natural circulation refers to the fact that the fluid in the boiler riser (upper pipe) absorbs the radiant heat of the furnace and is heated, so that part of the liquid (working fluid) evaporates into steam and forms a less dense mixture with the water that has not evaporated. The downcomer (downwater pipe) cannot absorb the radiant heat of the furnace outside the furnace, and the fluid density in the pipe is relatively high. Because of the difference in density, the driving force is generated between the two, forming a natural circulation without external force. The forced circulation method refers to the addition of a circulating water pump in the fluid circulation loop to provide driving force for the fluid. Therefore, compared with the two, the natural circulation method of feed water pump consumes less power and has been widely used at home and abroad.

As a traditional agricultural country, my country has a short industrial development history and slow development. My country's industrial development has just started when the industrial level of European and American countries has reached a certain level. Therefore, the quality of my country's boilers is also the reason that restricts the development of boiler control systems. In summary, combined with the current situation at home and abroad, my country's boiler control system has three main disadvantages: low self-control level, low fuel combustion efficiency, and unqualified boiler quality [2]. Combining the professional background, we can improve the boiler control system in two aspects: improving the level of automatic control of the boiler control system and improving the fuel combustion efficiency by improving the control system.

2. Process Analysis

2.1. Boiler

The boiler is composed of a steam drum and its accessories, various heating surfaces, headers and connecting pipes, steam and water system pipes and accessories, combustion equipment, flue gas pipes, frameworks (including platforms, escalators) and furnace walls. Boiler auxiliary equipment mainly includes water supply equipment, ventilation equipment, fuel supply and slagging and dust removal equipment, steam and water pipelines and accessories, as well as detection instruments and automatic control equipment.

2.2. Water Supply Equipment

The boiler is composed of water treatment equipment, water supply tank, and water supply pump. The boiler feed water treated by the water treatment equipment is boosted by the feed water pump, and then flows through the economizer to the steam drum and water wall. Water treatment equipment is used to remove impurities in water such as oxygen, calcium and magnesium ions, thereby avoiding scaling and corrosion on the inner wall of the boiler, ensuring the quality of boiler feed water and increasing the service life of the boiler [3].

2.3. Ventilation Equipment

The function of the boiler's ventilation equipment is to supply the air required for burning fuel and to remove the waste generated from the combustion in the boiler. In order to ensure the normal combustion, and make the flue gas flush the heating surface at a specified flow rate, and strengthen heat transfer [4]. Finally, a chimney with a certain height discharges the flue gas into the atmosphere to reduce smoke pollution and improve environmental sanitation.

2.4. Fuel Dust Removal Equipment

This is for the purpose of conveying fuel to the boiler, removing ash and slag and purifying flue gas, such as belt coal conveyor, ash conveyor, ash car and dust collector. For boilers that need to process the fuel in advance, it should also include fuel preparation such as screening, crushing, and coal grinding. In addition, the dust collector or flue gas desulfurization and denitrification device installed in the tail flue of the boiler is indispensable auxiliary equipment for reducing smoke pollution and protecting the environment [5].

2.5. Instrumentation and Automatic Control Equipment

In addition to the instruments installed on the boiler body such as water level gauges, pressure gauges and safety valves, in order to supervise, regulate and control the normal operation of boiler equipment safely and economically, a series of instruments, automatic boiler feed water adjustment devices, and automatic fuel combustion control equipment are often installed. Some boiler rooms are also equipped with industrial televisions and remote control devices and even more modern automatic control systems to supervise and control the operation of the boiler more scientifically [6].

2.6. Object and Process Analysis

SMPT-1000 (as shown in **Figure 1**) contains a variety of different industrial

Figure 1. SMPT-1000 training platform.

system units, such as centrifugal pump liquid level system, steam power deaeration system, heat exchange system, heating furnace system, industrial boiler system, etc. unit. The controlled object used this time is an industrial boiler system. Through the heating of the furnace, it exchanges heat with demineralized water to heat the demineralized water into superheated steam that meets the process requirements. The process flow is shown in Figure 2.

It can be seen from Figure 2 that the softened water passes through the water pump P1101 and then divides into two paths. A part of the water flows into the desuperheater. The purpose is to exchange heat with the superheated steam in the desuperheater to adjust the temperature of the superheated steam. At the same time, the superheated steam is also used for this. Part of the water is preheated. The other part of the water directly enters the economizer, and the water flowing through the desuperheater also enters the economizer. The water on the two lines merges in the economizer and exchanges heat with the high-temperature flue gas generated by fuel combustion, making full use of the flue gas. The residual heat is further preheated for the softened water.

The saturated water generated by economizer preheating first enters the steam drum and then enters the boiler water wall through the precipitation pipe to form a steam-water mixture by absorbing the furnace radiant heat. Due to the low density of the soda-water mixture, it returns to the steam drum for soda-water separation under the action of the density difference. The separation of steam and water is a very important function of the steam drum. The top of the steam drum is equipped with a vent valve, which exhausts the excess gas in the steam drum when the boiler is first heated. The vent valve is closed when the boiler is working normally. After the separation of the steam drum, the unvaporized part re-enters the water wall to absorb the heat radiation of the furnace, and the steam part enters the furnace again to heat up and become superheated

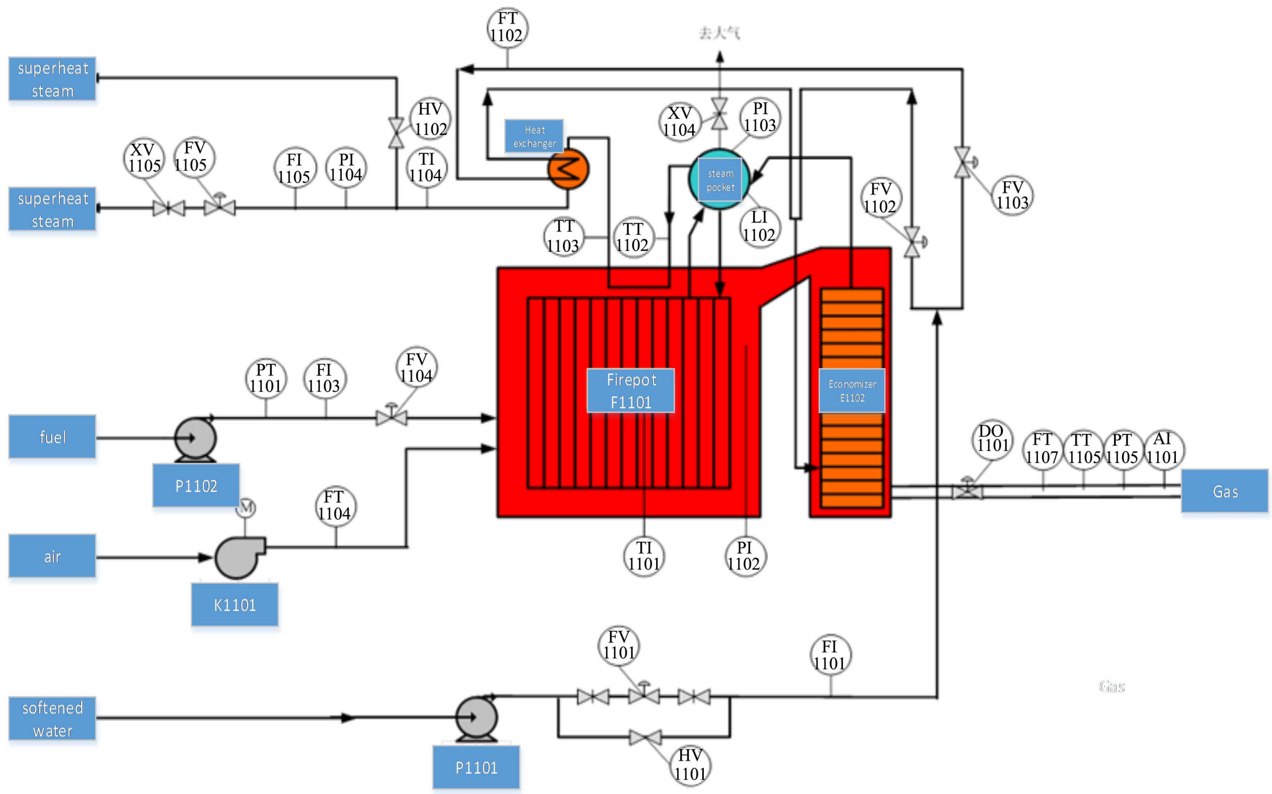

Figure 2. Process flow chart of natural circulation in medium pressure industry.

steam. The superheated steam enters the desuperheater, adjusts the temperature of the superheated steam and preheats the boiler water, and finally produces superheated steam that meets the technological requirements, and the superheated steam continues to be transported downstream.

Fuel and air are respectively sent to the combustor by a fuel pump and a frequency conversion blower in a certain proportion to provide energy for the transformation of demineralized water into superheated steam. The flue gas produced by combustion passes through the flue, is drawn out by the suction of the chimney, and finally discharged into the atmosphere.

3. Control System Design

According to the process requirements of the medium-voltage industrial natural circulation boiler control system, different control loops are designed for the above controlled variables. The single-loop control scheme is mainly used. The designed scheme is simple and easy to implement, and the system has certain resistance through repeated debugging.

The control system variable table is shown in Tables 1-5 and the control block diagram is shown in Figures 3-7.

The overall control scheme design of the boiler system can be represented by P & ID diagrams. P & ID (Piping and Instrumentation Diagram) diagram, also known as pipeline instrumentation flowchart. Through the pipeline instrument

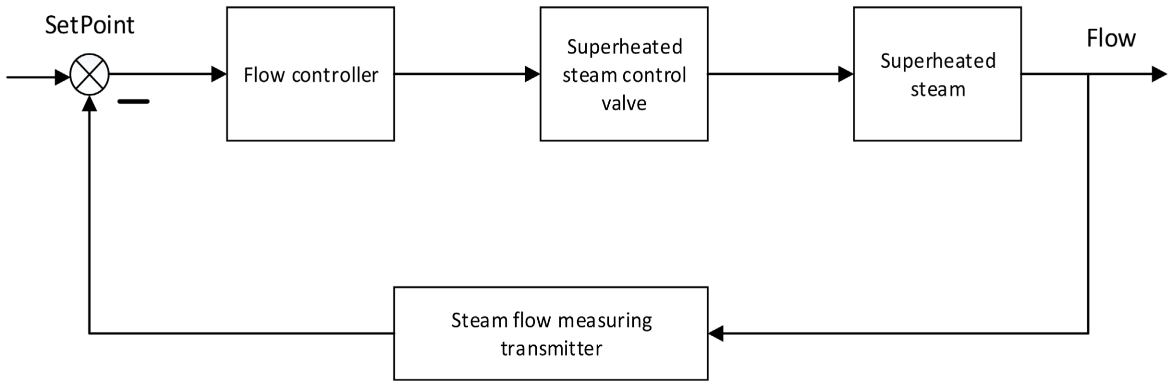

Figure 3. Block diagram of boiler superheated steam outlet flow control block diagram.

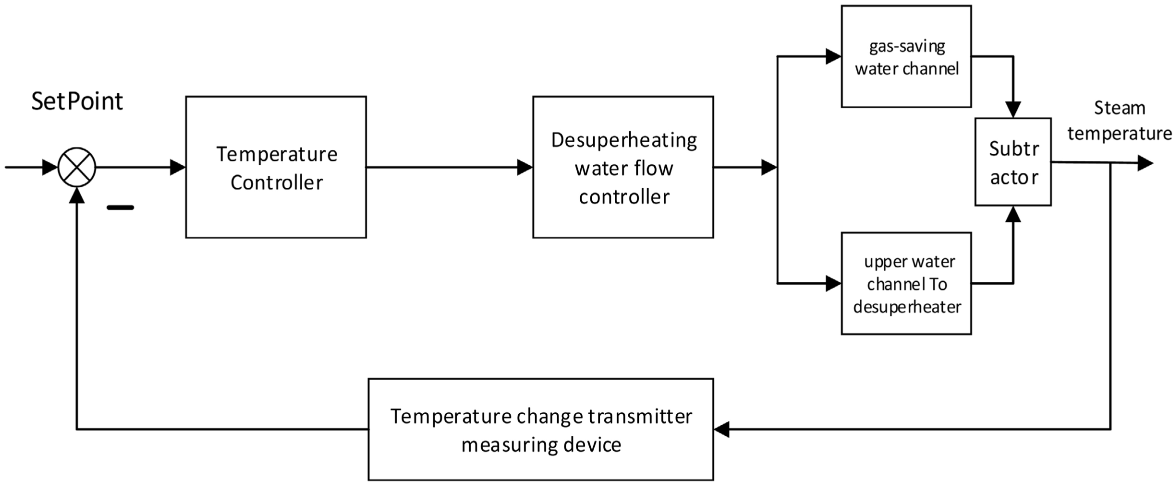

Figure 4. Block diagram of split-range control of superheated steam outlet temperature.

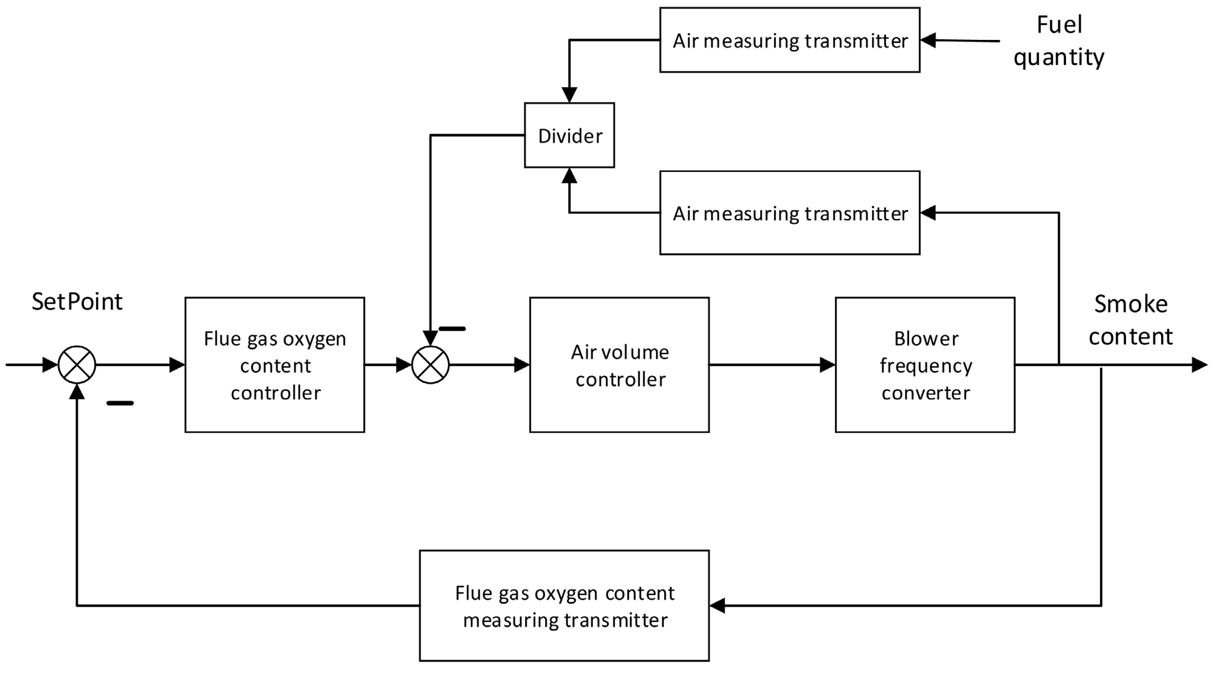

Figure 5. Block diagram of the control block diagram of the ratio of oxygen content in flue gas.

Table 1. Variable table of superheated steam outlet flow control system.

Project	Object
Controlled variable	Superheated steam flow
Manipulated variable	Superheated steam flow
Actuator	FV1105 Superheated steam flow line regulating valve
sensor	FI1105 Superheated steam flow sensor

Table 2. Variable table of superheated steam outlet temperature control system.

Project	Object
Main controlled variable	Superheated steam outlet temperature
Secondary controlled variable	Water volume to desuperheater
Manipulated variable	water volume to desuperheater, steam drum water volume to economizer
Actuator	FV1102 To economizer steam drum water supply pipeline regulating valve FV1103 to the steam drum water line regulating valve of the desuperheater
sensor	TI1104 superheated steam outlet temperature sensor

Table 3. Variable table of flue gas oxygen content variable ratio control system.

Project	Object
Main controlled variable	Flue gas oxygen content
Secondary controlled variable	Ratio of air volume to fuel volume
Manipulated variable	Air flow
Actuator	S1101 frequency conversion blower
sensor	AI1101 flue gas oxygen content, FI1103 fuel flow sensor, FI1104 air flow sensor

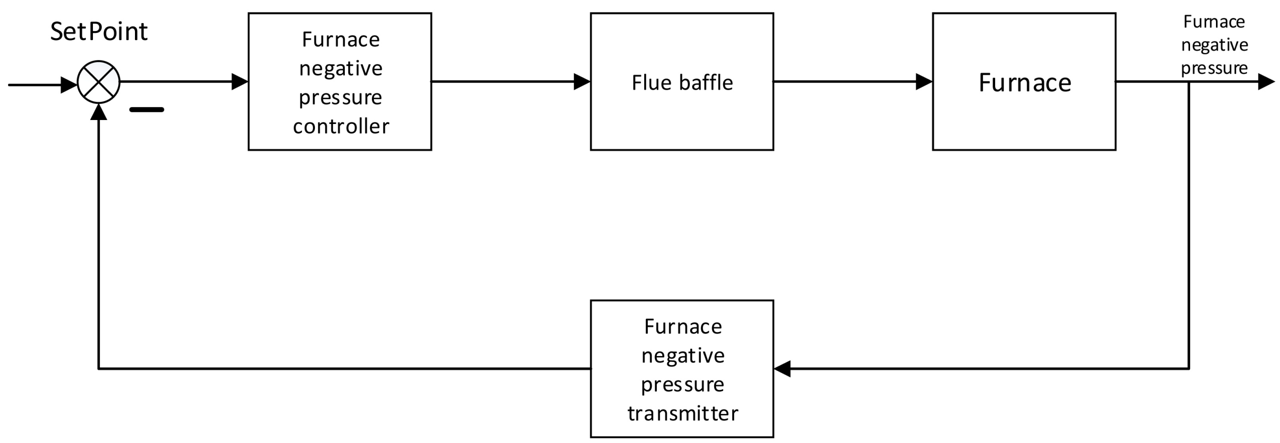

Figure 6. Block diagram of furnace vacuum degree control.

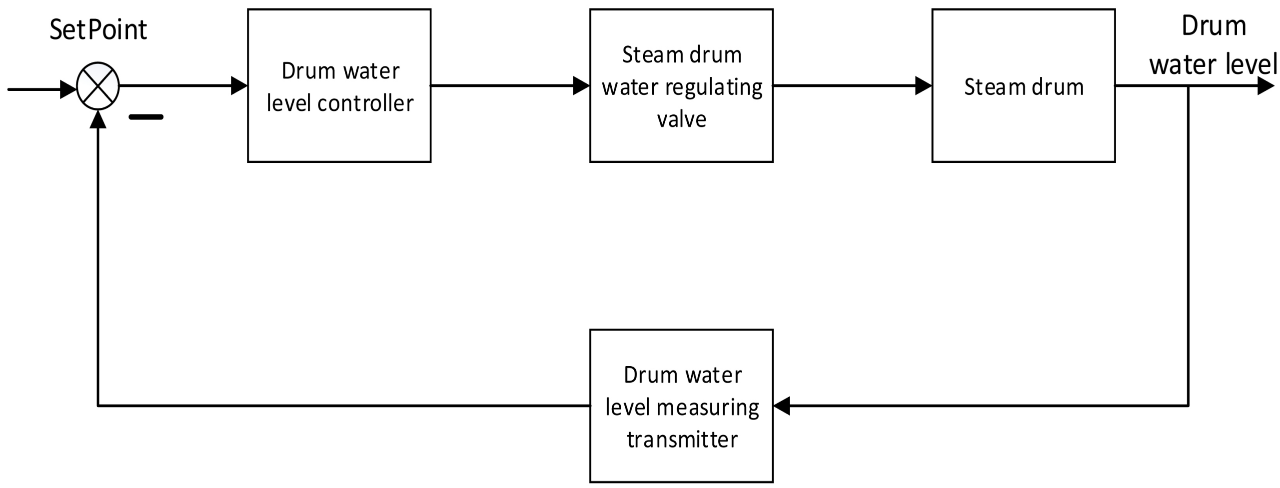

Figure 7. Block diagram of drum water level control.

Table 4. Variable table of furnace vacuum degree control system.

Project	Object
Controlled variable	Furnace pressure
Manipulated variable	Smoke volume
Actuator	DO1101 flue baffle
sensor	PI1102 Furnace Vacuum Sensor

Table 5. Variable table of drum water level control system.

Project	Object
Controlled variable	Drum level
Manipulated variable	Water flow rate on steam drum
Actuator	FV1101 steam drum water supply regulating valve
sensor	LI1102 steam drum water level sensor

flow chart, you can also clearly understand the control points of the system and the control plan of each control system. P & ID clearly and completely indicates all the process requirements in the engineering installation design, including the content and parameters of all equipment, piping and instruments. Through P & ID, the number, type and basic specification requirements of the instrument can be calculated; and the control methods of all equipment can be viewed according to P & ID, the corresponding number of I/O points can be calculated, and the basic interlocking method can be obtained. Based on the analysis of the natural circulation boiler process, the respective control systems are designed according to the selected controlled variables. The overall control plan P & ID of the boiler is shown in Figure 8.

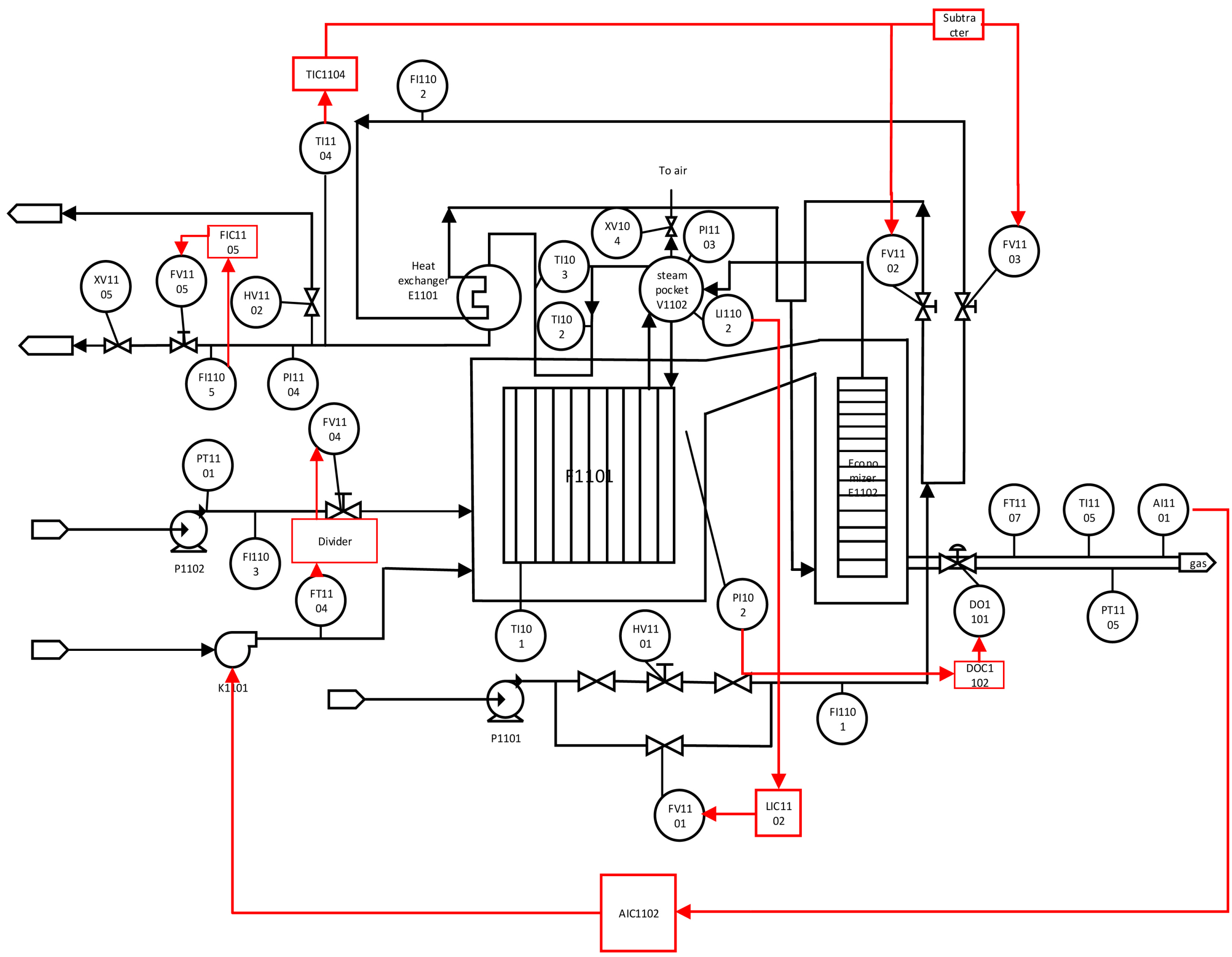

Figure 8. Pipeline instrument flow chart.

4. System Configuration and Programming

4.1. Continuous Function Chart Configuration

CFC (Continuous Function Chart) is a continuous function chart provided by Siemens PCS7 for continuous process control. A lot of function blocks are provided in CFC, such as: driver block, control function block, mathematical operation block, conversion block, operator control block, message block and advanced process control module, etc. Insert the function block into the organization block (OB) when in use, call the function block in the OB when the CPU starts, and determine the execution cycle according to the set value in the cyclic interrupt OB during operation. CFC can complete the multi-loop continuous control task. According to the natural circulation boiler system control scheme proposed in Chapter 3, the CFC configuration is used to realize the control of the natural circulation boiler, as shown in Figures 9-13.

In the flue gas oxygen content variable ratio control, the fan opening is used as the input of the controller, and the ratio of the air volume and the fuel volume is used as the setting value of the controller, and the ratio is realized by the division

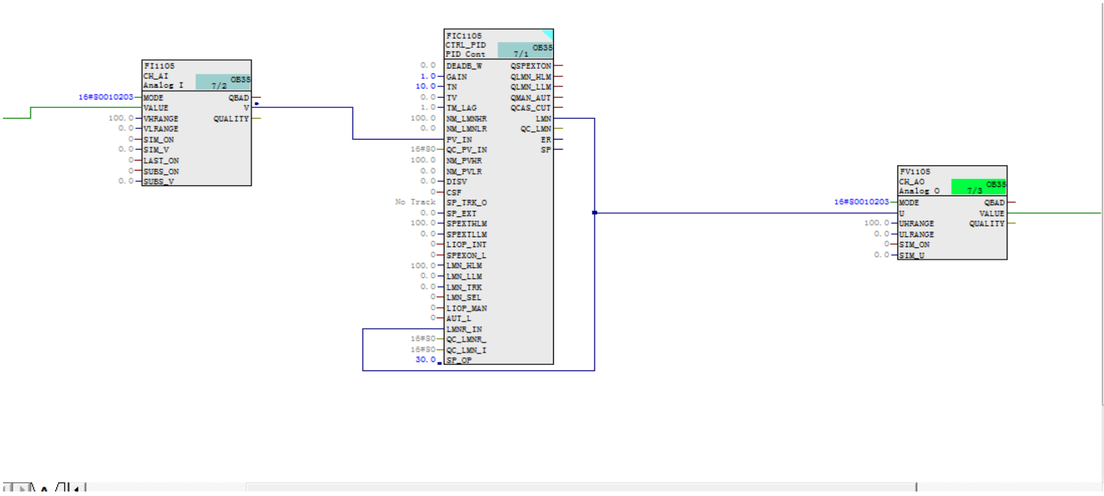

Figure 9. Single loop control configuration diagram of superheated steam outlet flow.

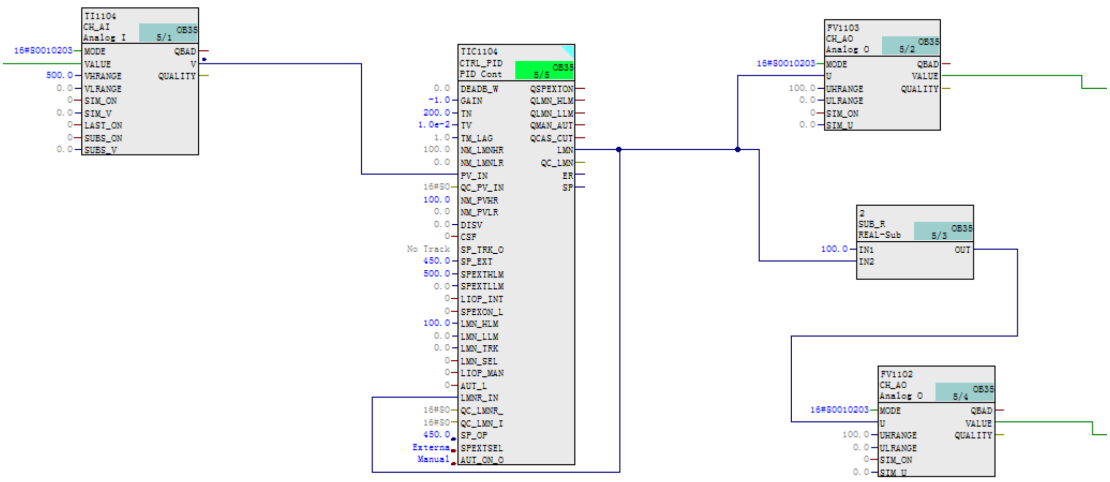

Figure 10. Single loop control configuration diagram of superheated steam outlet temperature.

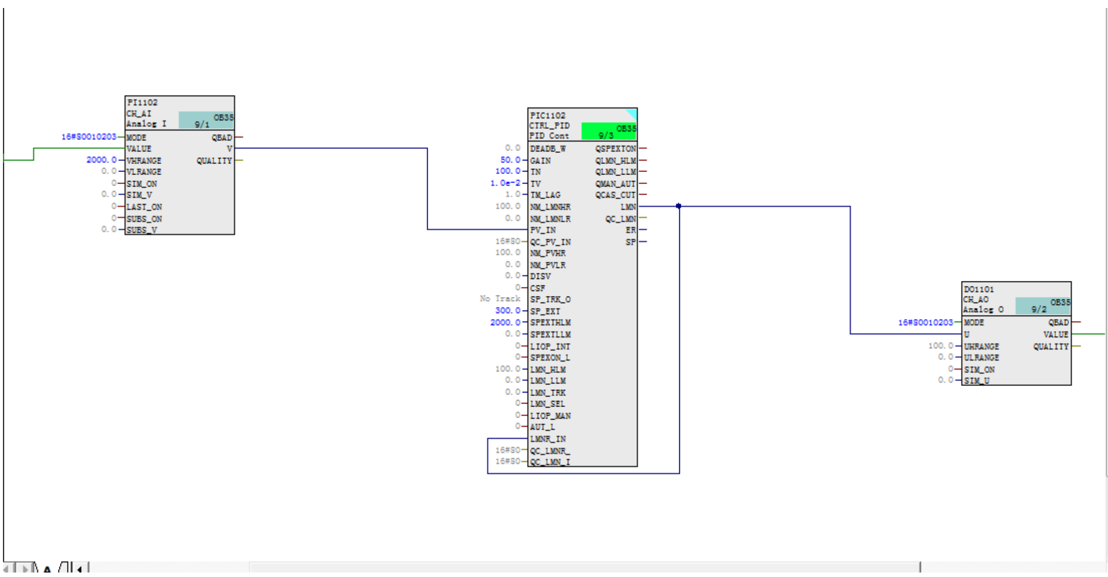

Figure 11. Single-loop control configuration diagram of furnace vacuum degree.

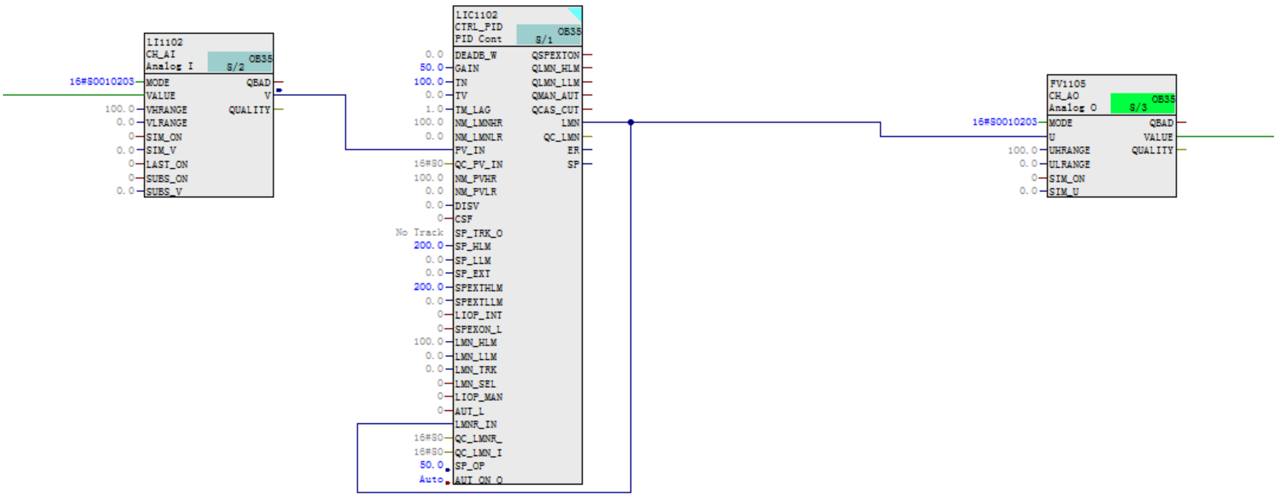

Figure 12. Single loop control configuration diagram of steam drum level.

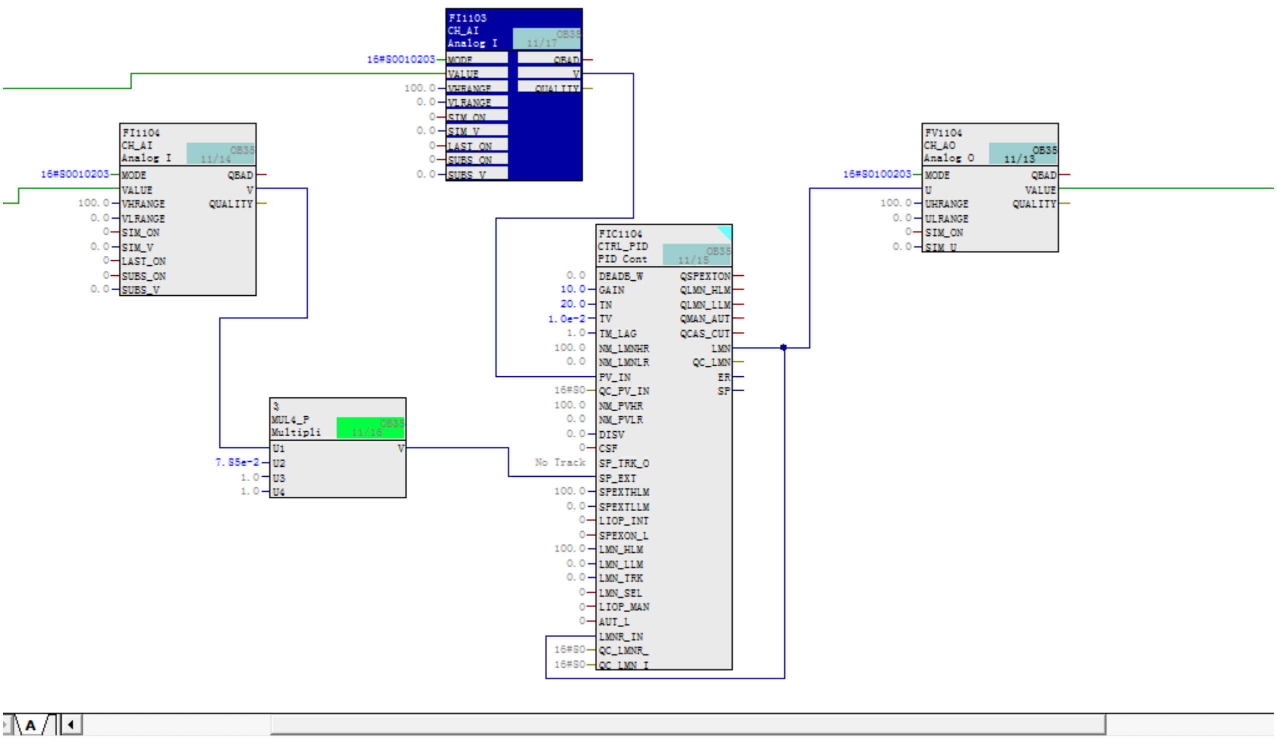

Figure 13. Single-loop control configuration diagram of flue gas oxygen content.

module (DIV_R). In the entire control loop, the oxygen content is maintained within a certain range by adjustment, so that the combustion condition is always maintained at the best state. Because the optimal ratio of fuel quantity to air quantity varies under different combustion conditions, the introduction of variable ratio control can make fuel more fully burned, and at the same time lose less heat, to achieve the purpose of energy saving and environmental protection.

4.2. Start-Up Sequence Flow Configuration

SFC (Sequence Function Chart) is a sequence function chart provided by Siemens PCS7, which realizes the step-by-step sequence control of the natural circulation boiler, which is used in the process of starting up and stopping. SFC configuration startup sequence diagram is shown in Figure 14.

The main idea of the start-up process is: first, ensure that all valves are closed and all parameters are in initial states; then, open the water filling valve to enter the water to stabilize the water level of the steam drum, and turn on the furnace negative pressure and flue gas oxygen content control loops in turn. , Switch automatically when the steam temperature reaches the required range; afterwards, keep the temperature stable and continue to increase the steam pressure, when the steam pressure reaches the required range, switch automatically, keep the temperature and pressure stable and continue to increase the load; finally, the superheated steam outlet flow the loop is cast automatically.

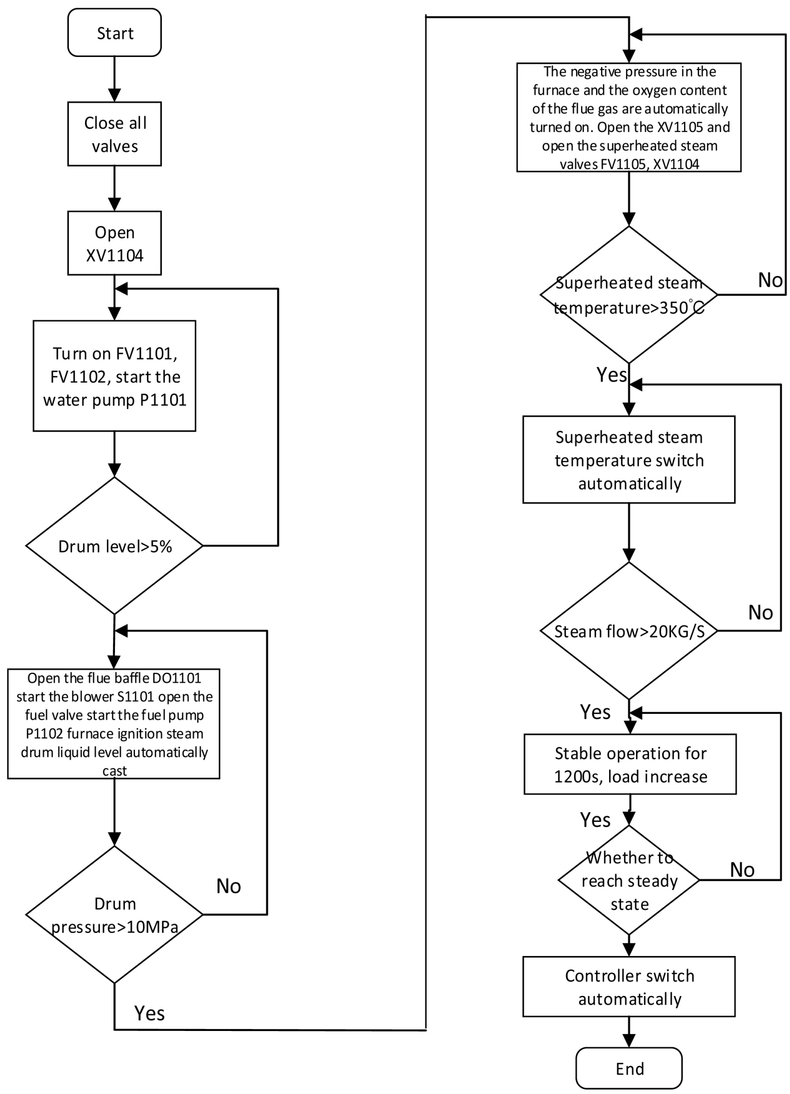

Figure 14. Start-up flow chart.

5. System Debugging and Discussion

In order to verify that the control system can run smoothly in a steady state, and has a certain degree of anti-disturbance, the process steps of increasing the load and reducing the load have been added in many tests as the disturbance of the control system. The lifting load requirement is that the outlet superheated steam flow rate is increased from 20 kg/s to 30 kg/s, and the reduction in compliance with the requirements is that the outlet superheated steam flow rate is reduced from 30 kg/s to 20 kg/s. After adding the above-mentioned disturbance function, the implementation effect of each index of the medium-voltage industrial natural circulation boiler control system is shown in Figures 14-19.

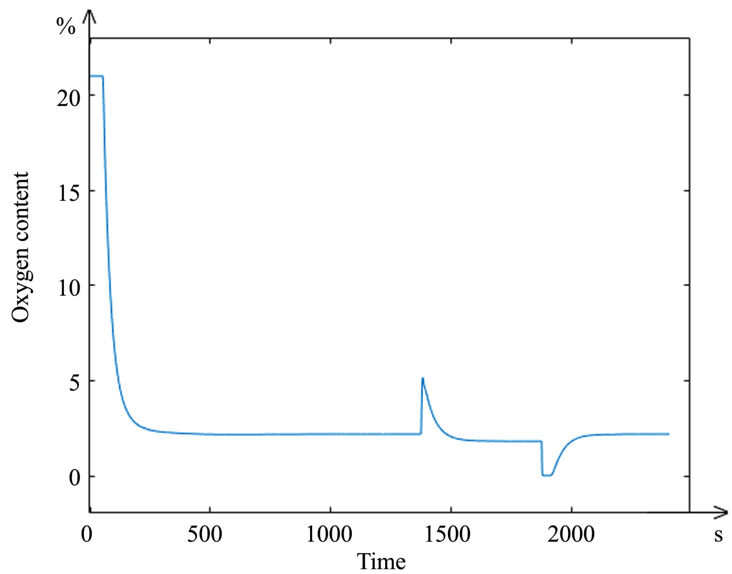

Figure 15. Curve of oxygen content in flue gas (X: second Y: %).

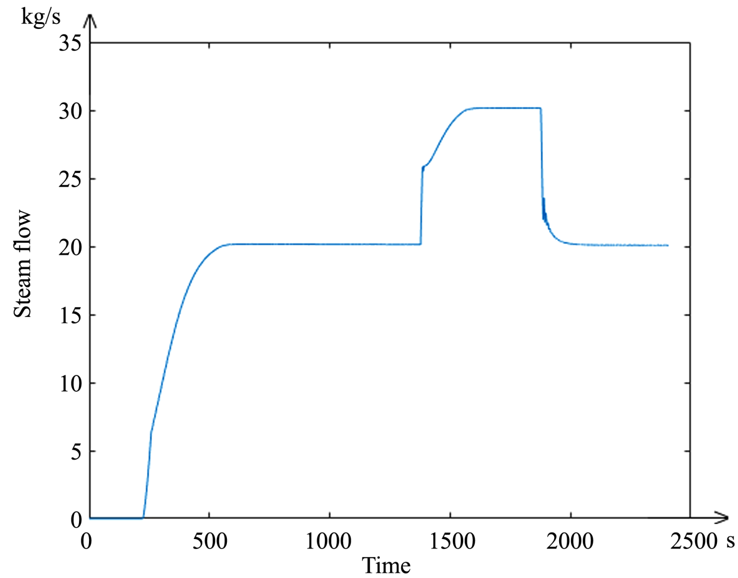

Figure 16. Curve of outlet superheated steam flow (X: second Y: kg/s).

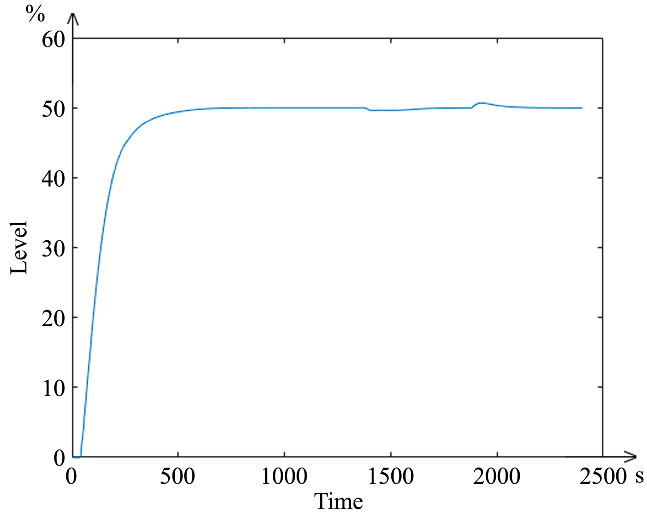

Figure 17. Drum liquid level curve diagram (X: second Y: %).

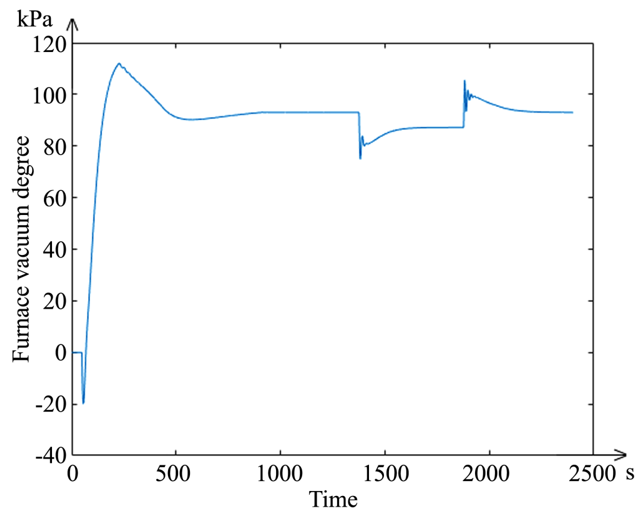

Figure 18. Furnace vacuum degree curve (X: second Y: kPa).

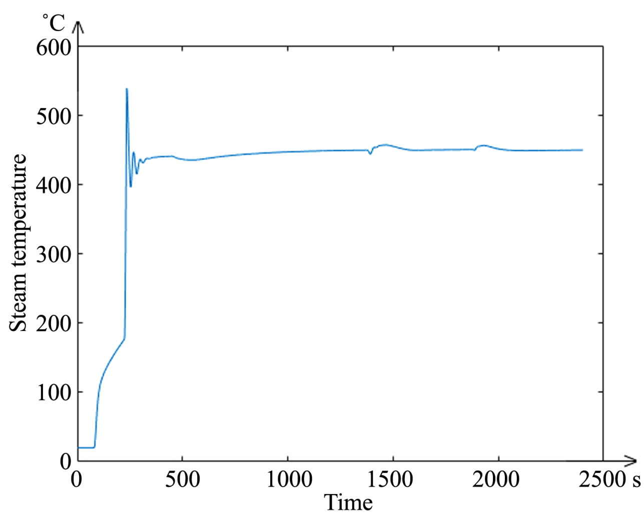

Figure 19. Temperature curve of superheated steam (X: second Y: ˚C).

Figure 15 shows the change of the flue gas oxygen content during the period from the initial start-up of the system to the stable operation of the system and the disturbance period. After the system is started, due to the combustion of fuel and oxygen, the oxygen content of the flue gas starts to drop sharply from 21% of the air oxygen content. In the initial CFC configuration, we obtained the air-fuel ratio through data review and several experiments: the air-fuel ratio in this control system is 1:0.0785. After the system runs smoothly for 1000 s, the system starts to increase the load. Due to the increase in system load, the amount of air and fuel increased accordingly, and the oxygen content of the flue gas used against it also changed due to the increase in air and fuel. Under PID control, the oxygen content of the flue gas returned to a stable state again in 250 s. After the system starts to reduce the load, the oxygen content of the flue gas changes accordingly, and finally returns to a stable state again.

Figure 16 shows the change of superheated steam flow during the period from the initial start-up of the system to the stable operation of the system and the disturbance period. In the figure, we can see that before the superheated steam valve is opened, the softened water inside the boiler has been heated to a certain temperature due to the preheating of the boiler. When the steam drum pressure reaches 1.0 MPa, the superheated steam valve is opened, and the flow of superheated steam is continuously increased. When the superheated steam flow reaches 15 kg/s, the superheated steam flow is automatically switched on. Under the control of PID, the superheated steam gradually stabilizes at 20 kg/s, and the system operates stably. After 1200 s of stable operation, the flow of superheated steam gradually reached 30 kg/s according to the requirements of lifting load, and the system became stable again. In the subsequent load reduction link, the outlet superheated steam is also reduced from 30 kg/s to 20 kg/s under the control of PID. It can be seen from the figure that the outlet steam flow has a very rapid changing trend during load reduction and load increase, showing a jump trend. In this case, a ramp function can be added to the CFC configuration, and the valve opening changes linearly.

Figure 17 shows the change of the drum level from the initial start of the system to the stable operation of the system. When the system starts, open the water supply valve and start the water supply pump. The softened water passes through the economizer channel and the softened water channel and finally enters the steam drum. Under system control, the steam drum level reaches 5% of the set value and starts to switch automatically, and finally stabilizes at 50% under system control. At 1400 s and 1800 s, due to the requirements of the system to increase the load and reduce the load, the drum level fluctuated, and the system returned to stability after a period of time.

Figure 18 shows the change of furnace vacuum during the period from the initial start-up of the system to the stable operation of the system. Furnace vacuum is an extremely important parameter standard. In order to ensure the normal operation of the boiler, the pressure in the furnace must be negative, that is, the vacuum of the furnace must be controlled. Otherwise, fire or fly ash may appear in the furnace, which may endanger the equipment in serious cases and personal safety. From the beginning of the system operation to the stable period of the system operation, the furnace vacuum is always maintained between 50 - 150 mm H_2O. In the case of the system's increasing load and decreasing load, the furnace vacuum degree fluctuates due to the coupling between the systems, but they all return to stability after a period of time.

Figure 19 shows the change of superheated steam temperature from the initial start of the system to the stable operation of the system. Since the initial temperature of the softened water is 104˚C, after the softened water enters the boiler, the temperature of the superheated steam starts to rise slowly. After the outlet valve is opened, the temperature of the superheated steam produced by the heated softened water rises sharply. Under PID adjustment, the opening of the upper water valve of the desuperheater changes to adjust the temperature of the superheated steam. Finally, it is stable at 450˚C in the state of stable operation and different disturbances.

6. Conclusions

In this paper, the medium-voltage industrial natural circulation boiler unit in SMPT-1000 is taken as the controlled object, and Siemens PCS7 is selected as its control system to control it. Based on the analysis of the process flow and characteristics of the controlled object, the control plan was designed according to the production process requirements, the system and equipment selection was completed, and the control plan was finally implemented. After programming and debugging, the following conclusions were obtained: 1) Medium after the design scheme of the natural circulation boiler control system of the pressure industry was implemented on Siemens PCS7, a good control effect was achieved. All parameters were controlled within the required range and the system was running smoothly, indicating that this scheme can meet the production requirements and has certain feasibility. 2) The sequence control program is designed so that the whole process of the system from cold driving to normal production can be automatically operated, and it can be stably upgraded when the system has a load lifting requirement, which improves the automation and safety of the system.

After a series of simulation experiments, we have obtained Figures 15-19. From the figures, we can see that the various control indicators of the boiler control system are within the control range, so it is concluded that the control system has a good control effect. In the experiment, we simulated the whole process of boiler operation, in which it took 800 seconds to drive the system in a cold state until the system run smoothly, and then the system run in a steady state to 1600 seconds to start increasing the load. In the case of the increase in compliance, the outlet steam flow rate increased from 20 KG/S to 30 KG/S in 250 seconds, and it had been running stably. Within 250 seconds, the other parameters have corresponding jitter changes, but they all return to a steady state after 250 seconds. For example, when the load is increased, the oxygen content of the cigarette increases greatly due to the increase of air fuel feed, but under the control of the correct air-fuel ratio, it gradually returns to the steady state and stabilizes at 1% - 3%. So we can make this system have good control stability.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Xu, L.L. (2014) Research on the International Competitiveness of My Country's Industrial Boilers. Henan University, Kaifeng.

[2] He, X.L. (2010) Discussion on the Current Situation of Industrial Boilers in My Country and the Countermeasures for Energy Saving and Emission Reduction. *Industrial Boiler*, No. 3, 1-8.

[3] Tian, X.W. (2014) Design of Boiler Cascade Three-Impulse Water Supply Control System Based on PLC. *Silicon Valley*, **7**, 19-20.

[4] Liu, X.P., Tian, L. and Liu, J.Z. (2009) Study on Characteristics of False Water Level of Boiler Drum. *Proceedings of the Chinese Society for Electrical Engineering*, **29**, 1-5.

[5] Wang, N.J., Shang, Q.Y., Zhang, X., Liang, X., Xiao, C.W. and Wang, Y.Y. (2016) The Practice of Pulverized Coal Industrial Boiler in Germany and the Status Quo and Development of Research and Development and Promotion in My Country. *Industrial Boiler*, No. 2, 1-10.

[6] Zhang, Q. (2015) Design and Implementation of Natural Circulation Boiler Control System Based on PCS7. China University of Petroleum (East China), Qingdao.