Energy Saving of Shuttle Kiln Furnace: A Study Based on PLC Control

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Abstract: In the production process of traditional shuttle kilns, energy consumption is high with serious pollution. Moreover, during its periodic operation, the heat loss is huge, and its material and energy are wasted seriously. Therefore, based on the traditional shuttle kiln, the shuttle kiln in this project is dynamically controlled by improving the control level of the kiln and the arrangement of burners. Thereby, the temperature in the kiln can be more evenly distributed, which can reach the ideal level during the firing process at the kiln temperature of 0-1200°C. Meanwhile, energy consumption increased by more than 30% year-on-year, and the temperature control accuracy is improved by more than 40%.

1. Introduction
The shuttle kiln control system proposed in this project directly controls the amount of gas entering the burner and the amount of combustion-supporting air through the temperature regulator, which also automatically adjusts the size of the air inlet of the burner and changes the ratio of air and gas to control temperature rise rate, constant temperature time and cooling rate, ensuring a good firing generation and meeting the production process requirements through PLC. Moreover, during the temperature rise process, due to the limited distribution of burners in the kiln, the firing time of the burners is uniformly and symmetrically controlled according to the size of the kiln, thereby generating a rotating airflow in the furnace to improve the accuracy and uniformity of temperature control.

2. Study on Energy-consumption

2.1. Thermocouple Aging
In the shuttle kiln, the main component of the thermal control sensor is the thermocouple whose main component is alumina that will produce tiny holes in a long-term high-temperature environment. The high-temperature gas generated in the kiln will enter the above-mentioned holes and corrode the thermocouple. After a series of chemical reactions, the aging phenomenon of the thermocouple will occur [1]. Therefore, when selecting thermocouples, tests and comparisons must be performed...
according to the requirements of the thermal engineering system.

2.2. Load Aging
After the silicon carbide rod is heated at high temperature in the air, it reacts with oxygen in the air to form SiO2, thereby accelerating the aging rate of the silicon carbide rod resistor. In the initial stage of the oxidation reaction, the surface layer of the silicon carbide rods forms a dense oxide layer. Then the conductive layer will slowly reduce, while the insulating layer will slowly increase, which will cause the internal overheating of the silicon carbide rod, greatly increasing the aging degree of the load.

2.3. Flue Gas Heat Loss
The heat in the discharged flue gas cannot be ignored, which can be recycled to the preheating of the auxiliary air, thereby improving the energy saving effect.

2.4. Efficiency Improvement of Heat Transfer
Mainly based on the electrical control technology, a rotating circulating airflow is formed in the kiln with the help of the firing process requirements, which improves the heat transfer efficiency and is more conducive to the firing of ceramic products.

3. Design of Kiln Temperature Control System

3.1. Framework of Control System
The monitoring system TPC can communicate and control the controller PLC, and the PLC can convert the temperature collected by the thermocouple to accurately control the gas and fuel air. As shown in Figure 1, the temperature in the kiln is accurately adjusted and controlled according to the temperature system. In addition, two important evaluation indicators in the control system are control accuracy and transient response capability [2].

![Figure 1 System framework](image)

3.2. Requirements of Temperature Control System
There are mainly four stages of control requirements in the temperature control system, namely safety detection stage → burner ignition start → shuttle kiln normal heating operation stage → operation alarm stage. In other words, controlling these four stages means the comprehensive application of controlling the temperature regulator in the temperature control link and the frequency conversion regulator in the process control link, and using signal acquisition and conversion in the signal control link.

In this project, the temperature is divided into 10 intervals according to the process requirements,
and the temperature is raised and lowered in stages, so that optimal results can be obtained. In the low temperature section (30-200℃), there is a certain temperature difference between the measured temperature in the kiln and the set temperature, but the actually measured heating rate is more consistent with the set heating rate trend. In the firing section (900-1150℃), the deviation between the set temperature in the kiln and the actual measured value is about 1.5℃. In the high heat insulation section (1150-1200℃), the deviation between the set temperature in the kiln and the actual measured value is about 2.5℃. In the cooling section (1200-300℃), the entire actual cooling rate in the kiln is more consistent with the set cooling rate. Therefore, in general, the actual temperature firing curve is more consistent with the set temperature firing curve.

4. Electric Control of Kiln

After determining the technological requirements of the firing process, it is defined that the control objects of the shuttle kiln are mainly temperature, pressure, and atmosphere. During the ceramic production, if there are no problems with the production raw materials or formulae, the success of ceramic firing often depends on the entire firing process. Moreover, when the automatic shuttle kiln burns ceramic products, many quantities need to be controlled, among which the most important one is to control the gas flow and combustion air flow. In addition, the temperature in the kiln detected by the thermocouple is converted into an electrical signal and fed back to the PLC, and then the PLC makes a control command to reach the temperature in the kiln.

According to the design requirements of this kiln, there are a total of four burners and S-type thermocouples. Meanwhile, Omron CP1H series programmable controller and the selected Weiluntong MT8121iE TPC are adopted to monitor the shuttle kiln control site in real time. When controlling the temperature in the kiln, the dual-adjustment control method of gas and auxiliary gas is applied to controlling the ratio of gas to air. After the thermocouple measures the temperature in the kiln, it sends the signal to the PLC, and then the PLC sends a control command to the gas actuator A for self-regulation. Next, the temperature signal fed back by the PLC will received, and the air actuator will self-adjust the opening of the gas actuator, so that the dual regulation control of the gas and the auxiliary gas by the two signals is realized, as shown in Figure 2, which improves the control efficiency and accuracy.\(^{[3-4]}\).

![Figure 2 Schematic diagram of dual actuator](image)

4.1. PLC and Peripheral Input Parts Control

This part is mainly to connect various input signals controlled by electricity such as safety alarm, manual adjustment, various monitoring and control on the temperature in the kiln, pressure, and wind speed with the PLC, as shown in Figure 3.
4.2. PLC and Peripheral Output Parts Control

This part is mainly to connect various output signals controlled by electricity such as safety alarms, actuator regulators, indicator lights, and the frequency conversion motor controlling the furnace with PLC, as shown in Figure 4.

Figure 3 PLC control input control wiring of kiln electrical

Figure 4 Control wiring of PLC control output in kiln electrical
4.3. Layout and Wiring of Electrical Control Board
The buttons and indicator lights in the control panel of the kiln are shown in Figure 5, and the wiring of the corresponding input and output with PLC is compact and orderly as shown in Figure 6.

4.4. Atmosphere Control Analysis
During firing, the more precise the atmosphere in the kiln is controlled, the better the color of the ceramic product after firing will be. The inner atmosphere of the shuttle kiln is mainly judged by the content of the oxidizing gas O2 and the reducing gas CO and H2 produced by the mixed combustion of gas and air. When the shuttle kiln is burned with an oxidizing atmosphere, the O2 content is more than 10%, while the CO content is about 5%, when the shuttle kiln is burned with a reducing atmosphere. Moreover, it has higher requirements on atmosphere firing system where the atmosphere should be controlled according to the rising temperature of the firing temperature system, and the atmosphere of the shuttle kiln is mainly controlled by dual actuators to control the amount of gas and combustion air entering the kiln. According to the atmosphere firing system as shown in Table 1, from the first stage to the third stage, the temperature range is from room temperature to 780°C, and the atmosphere is required to be an oxidizing atmosphere. When the temperature range of the fourth stage is 780-830°C, the atmosphere is required to be a weak reducing atmosphere. When the temperature range from the fifth stage to the sixth stage is 830-1150°C, the atmosphere is required to be an oxidizing atmosphere. When the seventh stage is 1150-1200°C, the atmosphere is required to be a reducing atmosphere [5].

Table 1 The firing temperature system of the shuttle kiln at each stage

| Stage name | temperature range/°C | Atmosphere system | Time /min | Heating rate /°C·min⁻¹ |
|------------|-----------------------|-------------------|-----------|-----------------------|
| 1          | Room temperature to 200 | Oxidation         | 330       | 0.5                   |
| 2          | 200 to 600            | Oxidation         | 480       | 1.0                   |
| 3          | 600 to 780            | Oxidation         | 180       | 1.0                   |
| 4          | 780 to 830            | Weak reduction    | 100       | 0.1                   |
| 5          | 830 to 900            | Oxidation         | 80        | 1.0                   |
| 6          | 900 to 1150           | Oxidation         | 180       | 1.0                   |
| 7          | 1150 to 1200          | Strong reduction  | 60        | 0.5                   |
| 8          | 1200 to 1150          | no                | 100       | -3.0                  |
| 9          | 1150 to 900           | no                | 200       | -1.5                  |
| 10         | 900 to 300            | no                | 550       | -1.3                  |

PLC controls the amount of gas and combustion-supporting air in the burner according to the feedback value of the temperature signal at each stage of the firing in the kiln. When the shuttle kiln is
firing in a certain temperature section, and the atmosphere is required to be an oxidizing atmosphere, the pressure ratio of the burner combustion air pipe and the gas pipe will be controlled according to the atmosphere system. Moreover, the adjustment of the atmosphere in the kiln is mainly controlled by the ratio of the opening of the valve on the gas pipeline and the opening of the combustion air valve by the dual actuator, thereby controlling the atmosphere in the kiln. Besides, from users’ feedbacks of the energy consumption ratio during use and the dynamic and symmetrical alternating operation of the burners in the kiln, it can be seen that the mixed gas sprayed by the four burners can strengthen the circulatory disturbance of the gas in the kiln. Therefore, modulating the burner of the shuttle kiln can make the atmosphere in the kiln reach uniformity faster. In addition, setting the atmosphere in the kiln actually determines the fuel-air pressure ratio of the powered burner, which also improves the quality of firing.

5. conclusion
The energy-saving data is not only to test results. More importantly, the feedbacks from users are more convincing. Moreover, the ultimate improvement of energy saving can be summarized as the optimized design of the control system and the scientific selection of each control device. The specific points are as follows: (1) The PLC controls the amount of gas and combustion-supporting air in the burner according to the feedback value of the temperature signal at each stage of the kiln. When the shuttle kiln is firing in a certain temperature section, the pressure ratio of the burner combustion air pipe and the gas pipe will be controlled according to the atmosphere system, if the atmosphere is required to be oxidized. Besides, the adjustment of the atmosphere in the kiln is mainly controlled by the ratio of the opening of the valve on the gas pipeline and the opening of the combustion air valve by the dual actuator, thereby controlling the atmosphere in the kiln. (2) From the dynamic symmetrical alternating operation of the burners in the kiln, it can be seen that the mixed gas emitted by the four burners can strengthen the cyclic disturbance of the gas in the kiln. Therefore, modulating the shuttle kiln burner can make the atmosphere in the kiln more uniform. Meanwhile, the quality of firing is also improved.

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