Design of Heat Exchange System of Sand Core Drying Furnace

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Abstract. Heat exchange system is a circulatory drying system on sand core drying furnace. However, there are some shortcomings in the heat exchange system of sand core drying furnace in the current industrial field. For example, the temperature in the drying process is not stable enough, and the optimal temperature control parameters are difficult to choose. In this study, a proportional regulating heat exchange system is designed. The system adopts SIMATIC 1200 programmable logic controller as controller, motor-driven control valve as actuator and back propagation neural network proportion integral differential control algorithm. After sand core drying test, the results revealed that the proportional regulating heat exchange system can realize automatic control of sand core drying temperature and output the optimal combination of heat exchange system control parameters. Compared to the previous heat exchange system, it has better drying temperature control stability.

Keywords: heat exchange system; drying temperature; proportional regulation; back propagation neural network; proportion integral differential control.

1. Introduction
Sand core drying furnace is a kind of convection drying equipment, mainly used for drying the casting sand core after the surface is soaked with paint [1]. Sand core drying furnace produces circulating air at a certain temperature through heat exchange system to carry out jet drying of sand core [2]. At present, the heat exchange system is usually composed of proportion integral differential (PID) temperature controller and integrated burner in the industrial field. By using PID temperature controller with pulse width modulation (PWM) output, this system controls switching time of gas and air solenoid valve in a duty cycle, so as to control the drying temperature. However, in the industrial field, the design has exposed some shortcomings. This heat exchange system has a high construction cost. And it is very difficult to select PID control parameters. When PID parameters are not selected properly, the drying temperature will fluctuate more than 5 °C.

According to the shortcomings of pulse control heat exchange system, a proportional control heat exchange system is designed. The heat exchange system uses back propagation (BP) neural network to output the optimal PID parameter combination [3], and adopts SIMATIC 1200 programmable logic controller (PLC) to drive the motor-driven control valve to adjust the gas and air flow in proportion. The
purpose of this design is to improve the stability of drying temperature control and reduce the construction cost of heat exchange system.

2. Principle Of Sand Core Drying Furnace
Sand core drying furnace has a hollow structure, which consists of furnace body, heat exchange system, cooling system and roller conveyor line. Furnace body has good heat preservation function, divided into drying area and cooling area. The heat exchange system is arranged on the top of the drying area of the furnace body for better safety. During drying operation, the heat exchange system generates air circulation between the heat exchanger and the furnace through the air circulating blower, which has a large air volume, and it heats the circulating air through gas combustion, so as to achieve jet drying of the sand core in the furnace. The cooling system is arranged on the top of the cooling area of the furnace body, and the circulating cold air is formed between the outdoor and the furnace by using the exhaust blower and the cold air blower to cool the sand core after drying. The function of the roller conveyor line is to transport the sand core through the drying area and cooling area orderly, so as to realize the drying of the sand core.

3. Design of Proportional Regulating Heat Exchange System

3.1. System Hardware Design
In general, the hardware design of proportional regulated heat exchange system is shown in Fig.1. The system is mainly composed of heat exchanger and electrical control.

The heat exchanger is composed of burner, motor-driven control valve, air-fuel proportional control valve, gas solenoid valve, combustion-supporting blower, air circulating blower and so on. As shown in Fig.1, the combustion-supporting blower blows the air in the heat exchanger into the bellows in the furnace, and evenly blows it into the lower furnace through the tuyere and forms negative pressure in the heat exchanger. The air in the furnace return to the heat exchanger through the return tuyere, so that the circulating air is formed between the heat exchanger and the furnace. The heat needed for circulating air heating comes from gas combustion. To control the drying temperature, control the ratio of gas to air and flow is the best way. Therefore, the gas and air supply lines are designed.

On the air supply line, the combustion-supporting blower blows air into the pipeline. The motor-driven control valve can be set in the opening range of the valve, the opening range is set to 15° − 75°. The opening of motor-driven control valve is adjusted proportionally according to the 4-20mA current signal output by PLC. The opening of motor-driven control valve is at the minimum opening of 15 without input current signal. Butterfly valves limit the maximum flow of air.

On the gas supply line, gas solenoid valve through the program to control the opening or closing of the gas supply. Gate valves limit the maximum flow of gas. Based on the current air intake pressure, air-fuel proportional control valves provide the gas pressure required for combustion in accordance with the air-fuel ratio. Finally, the gas mixed with air in accordance with the air-fuel ratio is mixed and burned at the burner, and the circulating air is heated. In this way, the drying temperature of the drying furnace can be controlled.
The electrical control part adopts SIMATIC PLC S7-1200, analog input and output modules as the controller, and adopts monitor and control generated system (MCGS) human machine interface (HMI), ignition controller, ignition transformer, temperature transmitter, PT100 temperature sensor and other hardware components. The process data such as drying time and temperature are stored in MCGS HMI, which can be sent to PLC by users. After receiving the ignition command of PLC, the ignition controller controls the gas solenoid valve to open, controls the ignition transformer to generate electric sparks on the ignition electrode of the burner and ignites the mixed gas. When PT100 temperature sensor gives real-time temperature feedback to SIMATIC S7-1200 PLC, PLC outputs 4-20mA signal to electric...
regulating valve according to BP neural network PID algorithm. Electric control valve according to the 4-20mA signal on their own opening proportional adjustment, at the same time its own actual opening feedback back to PLC.

When the drying temperature of sand core is higher than the set temperature, the opening of the electric regulating valve decreases, the burning power of the burner decreases, and the temperature decreases; When the drying temperature of the sand core is low, the opening of the electric regulating valve increases, the flow increases, and the drying temperature rises, so as to realize the stable control of the drying temperature of the sand core. Drying temperature control process of heat exchange system is shown in Fig.2.

3.2. Design of Control Algorithm

The heat exchange system of drying furnace has the characteristics of nonlinear, large hysteresis and multi interference. It is difficult to obtain the optimal control parameters and good control effect when using single PID control. BP neural network has good self-learning and self-adaptation ability. Therefore, combining BP neural network with classical PID control can improve the stability of drying temperature control by adjusting PID control parameters in real time [4], through BP neural network's self-learning and self-adaptation ability. The control principle of the system is shown in Fig.3.

When the proportional regulating heat exchange system controls the motor-driven control valve, it adopts the incremental PID controller to output the increment of the opening of the electric regulating valve and adjust the opening.

The neural network of the system adopts a three-layer network structure, with 1 hidden layer, 5 hidden layer neurons and 3-5-3 network structure, as shown in Fig.4.

The proportional integral differential coefficient of PID control cannot be negative, so the output layer activation function of the neural network uses a non-negative Sigmoid function, and the hidden layer activation function uses a positive and negative symmetrical Sigmoid function [5]. The input and output of the input layer of BP neural network are as follows:

\[ O^{(1)}_j(k) = x_j(k) \quad (j = 1,2,3) \]  

The input and output of the hidden layer and output layer of the BP neural network are as follows:

\[
\begin{align*}
\text{net}^{(2)}_i(k) &= \sum_{j=1}^{3} w^{(2)}_{ij} O^{(1)}(k) \quad (i = 1,2,3,4,5) \\
O^{(2)}_i(k) &= f\left(\text{net}^{(2)}_i(k)\right) \\
\text{net}^{(3)}_l(k) &= \sum_{i=1}^{5} w^{(3)}_{il} O^{(2)}_i(k) \quad (l = 1,2,3) \\
O^{(3)}_l(k) &= g\left(\text{net}^{(3)}_l(k)\right)
\end{align*}
\]

In the article above, superscripts (1), (2) and (3) separately represent the input layer, hidden layer and output layer of BP neural network, \( w^{(2)}_{ij} \) and \( w^{(3)}_{il} \) respectively represent the weight coefficients of hidden layer and output layer. And \( x_1(k) = r(k) \) is the system setting drying temperature, \( x_2(k) = y(k) \) is the actual drying temperature, and \( x_3(k) = e(k) \) is the temperature deviation. The output layer output adjusts the PID control parameters, there are \( O^{(3)}_1(k) = k_p; \ O^{(3)}_2(k) = k_i; \ O^{(3)}_3(k) = k_d. \)
During the back-propagation process of BP neural network error, the temperature error square is selected as the system performance index, which is searched and adjusted according to the direction of negative gradient of weight coefficient, and an inertia term is added to minimize the global fast convergence of search [6].

\[
E(k) = \frac{1}{2} (r(k) - y(k))^2
\]

(4)

The weight coefficients of the output layer are adjusted as follows:

\[
\Delta w_{i}^{(3)}(k) = -\eta \frac{\partial E(k)}{\partial w_{i}^{(3)}} + \alpha \Delta w_{i}^{(3)}(k-1)
\]

(5)

Where: \( \eta \) is the learning rate; \( \alpha \) is the inertia coefficient. The weight coefficient adjustment algorithm of the output layer and the hidden layer is available [7]:

\[
\begin{align*}
\Delta w_{i j}^{(3)}(k) &= \eta O_{j}^{(2)}(k)\delta_{i}^{(3)} + \alpha \Delta w_{i j}^{(3)}(k-1) \\
\delta_{i}^{(3)} &= e(k) \text{sgn}(\frac{\partial y(k)}{\partial u(k)}\frac{\partial u(k)}{\partial O_{j}^{(3)}(k)} g'(net_{i}^{(3)}(k)))
\end{align*}
\]

(6)

\[
\begin{align*}
\Delta w_{i}^{(2)}(k) &= \eta O_{j}^{(1)}(k)\delta_{i}^{(2)} + \alpha \Delta w_{i}^{(2)}(k-1) \\
\delta_{i}^{(2)} &= f'(net_{i}^{(2)}(k))\sum_{l=1}^{n} w_{j l}^{(3)}(k)\delta_{l}^{(3)}
\end{align*}
\]

(7)

4. Test Verification And Result Analysis
The physical object of proportionally regulated heat exchange system of sand core drying furnace built in a casting factory is shown in Fig.5. Drying test was carried out on sand cores soaked with paint in the
factory. According to the process requirements, the drying temperature of the casting sand core is 150°C and the drying time is 30 min. The temperature data of the drying process is stored on the disk in HMI at intervals of 15s.

In the test, the operation process of sand core drying is as follows: Firstly, the combustion fan is turned on to purge the furnace, and then the burner heats up. When the drying temperature reaches the target set temperature, the empty furnace is tested for 80 min at constant temperature. After that, the sand core was successively placed on a tray and transported to the furnace. The sand core was continuously dried for 80 min. Finally, the furnace was blown to cool down and the equipment was shut down after the operation.

Fig. 5 The actual heat exchange system and its burner

![The actual heat exchange system and its burner](image)

Fig. 6 Temperature change curve of sand core drying

![Temperature change curve of sand core drying](image)

Fig. 7 Error change curve of sand core drying temperature

At the end of the test, the temperature record data of the disk was exported by HMI script function, and the sand core drying temperature change curves of the two heat exchange systems were obtained, as shown in Fig.6.

It can be seen from Fig.6 that when the BP neural network PID control is adopted, the rise time and adjustment time of the heat exchange system are shorter, the response is faster, the overshoot is smaller, and the response characteristics are better. Secondly, after reaching the set drying temperature, the temperature fluctuation is smaller and the temperature control is also more stable during the constant temperature stage of the empty furnace.
During continuous sand core drying, PID control and BP neural network PID control were used to control drying temperature. The comparison of drying temperature errors between the two is shown in Figure 7. The results show that the temperature error of continuous sand core drying is $\pm 3 ^\circ C$ when PID control temperature is adopted. When BP neural network PID is used to control the temperature, the temperature error of continuous sand core drying is only $\pm 0.7 ^\circ C$, the fluctuation of sand core drying temperature is smaller, and the control of drying temperature is more stable.

5. Conclusion
By using SIMATIC PLC S7-1200 controller, motor-driven control valve, other hardware and BP neural network PID control algorithm, a proportional regulating heat exchange system is designed. This heat exchange system realizes the proportional regulation of gas and air inlet flow. The system can stably control the temperature of sand core drying, the system design is correct.

The results of sand core drying test show that the proportional regulating heat exchange system based on BP neural network PID has a faster response characteristics. During constant temperature operation and continuous core drying operation, its temperature fluctuation range is smaller, and it has better temperature control effect.

Proportional regulating heat exchange system adopts BP neural network to output optimal control parameters, which solves the problems of poor temperature stability and wide range of drying temperature fluctuation in heat exchange system. The drying test shows that the proportional regulating heat exchange system has good temperature control result and has great value of popularization and application.

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