The Temperature Control System of Continuous Diffusion Furnace

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Abstract: The diffusion furnace is an important and indispensable equipment in the production process of solar cell, it plays a crucial role in the photoelectric conversion efficiency of the solar cell. Production efficiency and temperature control precision of traditional closed diffusion furnace is low. To solve this problem, this paper presents a temperature control system of continuous diffusion furnace. The system uses PID cascade control algorithm based on Smith estimating pre-compensation to achieve the temperature control of furnace and ensure the uniformity and stability of the temperature, so as to ensure the uniformity of the dopant diffusion. The simulation results verify the effectiveness of the control algorithm; and practical experiments prove the feasibility of the temperature control system.

1 INTRODUCTION

Solar panel as the core part of the solar photovoltaic power generation (Cao et al., 2013), it can convert the solar energy into electric energy stored in batteries and promote the work load. In the whole production process of solar cells, P-N junction process (Wang et al., 2012) is a crucial step, it is related to the conversion efficiency of crystalline silicon solar cells and the precision and stability of the process temperature control directly affects the quality of P-N junction. So the diffusion furnace is indispensable important equipment in solar cell production process, the temperature control accuracy and the stability of the system are very important.

According to the requirements of the automatic control temperature, PID control, cascade control (Gervini and Perondi, 2014), Smith estimating pre-compensation (Ma et al., 2014) and compound control among them have gradually replaced the traditional PID control. At present, temperature control technology of diffusion furnace equipment in some foreign companies is more advanced, such as Germany's BTU (Anonymous, 2008), the United States' CENTROTHERM (Yan et al., 2012) and so on. In recent years, the domestic diffusion furnace equipment develops quickly in upgrading and technology, but compared with the international advanced diffusion furnace equipment, there is still gap.

Diffusion furnace mostly adopts the method of resistance heating to heating; the temperature control system contains one order inertial link with pure hysteresis. The link has characteristics with big inertia, pure lag and nonlinear, and it is difficult to use mathematical method to establish model and determine the parameters. And now the temperature control precision requirement of diffusion furnace is higher, the traditional furnace temperature control system cannot meet the requirements. This paper designs a continuous diffusion furnace that uses PID cascade control algorithm based on Smith estimating pre-compensation to guarantee the uniformity and stability of the temperature, so as to ensure the uniformity of the dopant diffusion, and to improve photoelectric conversion efficiency of silicon (Olsen 2012).

2 DESIGN OF CONTINUOUS DIFFUSION FURNACE

As shown in Figure 1 is diffusion process of continuous diffusion furnace, it is divided into two steps:

1) Quartz boat 4 carrying silicon wafers is put on the left paddle 1 and loaded into furnace tube 2 of diffusion furnace from left. Right paddle 5 goes into furnace tube 2 from the right and stop go forward when it arrives constant temperature area 3. Left

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paddles 1 stop go forward when quartz boat arrives at central region of constant temperature area 3.

2) The left paddle 1 failing by elevating mechanism and handover quartz boat on it to right paddle 5. Then left paddle 1 exits form furnace tube 2 and rises to the original position to reload the silicon wafer. And right paddle 5 exits slowly from constant temperature area 3, when the left side silicon wafer on the quartz boat 4 exits from the constant temperature area 3, the right paddle 5 exits from diffusion furnace tube 2 and waiting to unload the quartz boat 4.

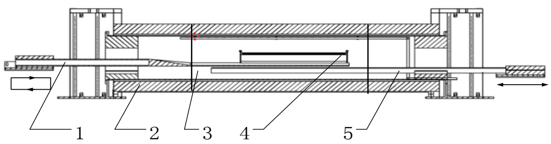


Figure 1: Diffusion process of continuous diffusion furnace.

Where 1-Left paddle
2- Furnace tube
3- Constant temperature area
4- Quartz boat
5- Right paddle

According to working process, the mechanical structure design of the equipment is shown in Figure 2. The overall system of the continuous diffusion furnace comprises 5 parts: a purification cabinet, a gas source cabinet, a control cabinet, a resistance heating furnace cabinet and a transfer system. The equipment profile dimension is about 7480 (mm) * 1200 (mm) * 1500 (mm).

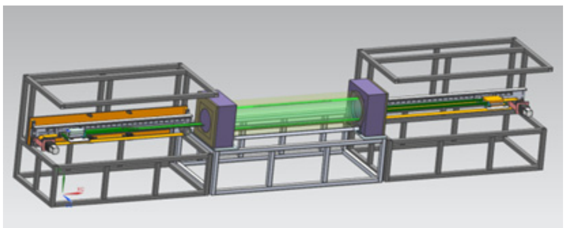


Figure 2: The mechanical structure of continuous diffusion furnace.

3 TEMPERATURE UNIFORMITY ANALYSIS OF CONTINUOUS DIFFUSION FURNACE

In order to design temperature control system, determine distribution ways of heating furnace wire and whether need air curtain in the ends of furnace tube, we need further analyze temperature distribution of the diffusion furnace. The FLUENT is used to modeling and simulation, the numerical simulation analysis for the furnace temperature of continuous diffusion furnace to get a better temperature control method.

3.1 Establish Geometric Model of the Continuous Diffusion Furnace

In this paper, we mainly study the temperature distribution of continuous diffusion furnace, so select reaction chamber of the diffusion furnace as the research object. The geometric model of continuous diffusion furnace as shown in Figure 3, it mainly consists a feeding mechanism, the furnace cavity, air curtain device, windpipe etc. And there are three airway distributed in same angle along the axial direction of diffusion furnace.

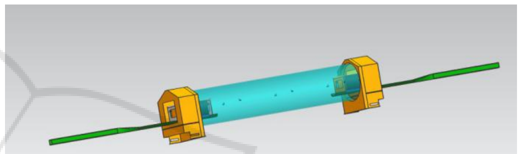


Figure 3: Geometric model of the continuous diffusion furnace.

Grid division is the first step, the areas of the oven cavity and furnace door all using tetrahedral meshes, the Tet/Hybird grid type and internal grid size is 10mm, as shown in Figure 7. The equations of the model are solved by using the continuous equation, momentum equation and energy conservation equation.

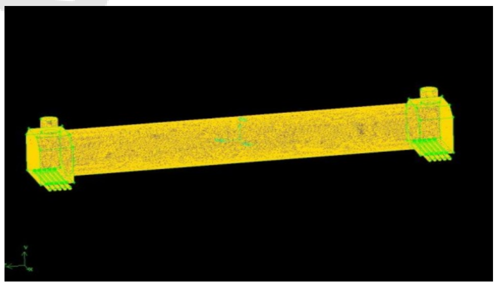


Figure 4: Grid division of the continuous diffusion furnace.

3.2 Set Physical Parameters and Boundary Conditions

There are two types of heat exchange between the inner wall of the furnace tube and the air inside the furnace tube: one is the heat convection between each other; another is heat transfer by radiation from inner wall of furnace tube to air inside furnace tube. Thus， according to the actual situation of the continuous diffusion furnace, the boundary conditions and physical parameters are adopted as follows：

1) Set outer wall of the continuous diffusion furnace as coupled wall; Set inner wall surface as convection heat transfer and radiation wall; Set Internal and external wall material as silicon dioxide.

2) Set temperature of furnace mouth without air curtain as 730K.

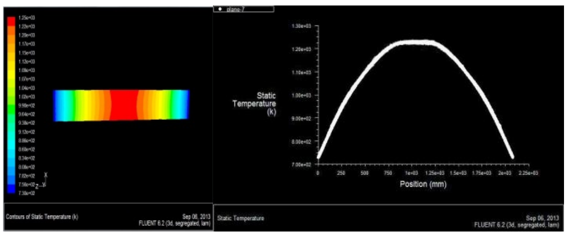
3) Set air intake velocity of air curtain as 1m/s, temperature is 730K; the relative pressure of outlet surface is 0Pa;

4) Air density is 1.225K/ m3, the coefficient of viscosity is 1.789×e-0.5kg/m·s, the coefficient of thermal conductivity is 0.1242W/m • k, the specific heat of air is 1006.43J/kg • K.

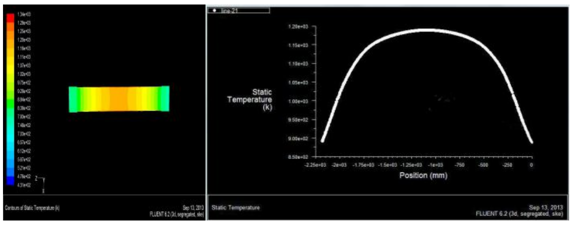
3.3 Analysis of Numerical Simulation Results of Temperature Field

In order to realize better distribution of temperature field in furnace cavity of continuous diffusion furnace, conditions that furnace mouth without air curtain or with air curtain are compared respectively by 3-zone heating and 5-zone heating. The temperature distribution in the furnace is simulated by using the FLUENT to simulate the three-dimensional temperature of the geometry model, as shown in figure 5.

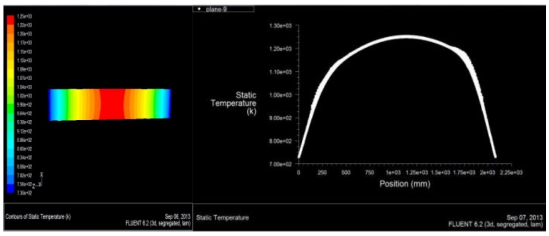
In Figure 5, (a) is temperature simulation result of continuous diffusion furnace without air curtain and heated by 3-zone hennaing; (b) is temperature simulation result of continuous diffusion furnace with air curtain and heated by 3-zone hennaing; (c) is temperature simulation result of continuous diffusion furnace without air curtain and heated by 5-zone hennaing; (d) is temperature simulation result of continuous diffusion furnace with air curtain and heated by 5-zone hennaing.



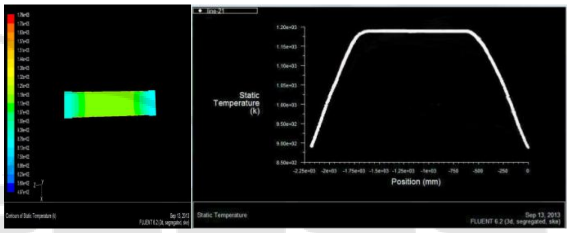
(a) Temperature simulation result of continuous diffusion furnace without air curtain and heated by 3-zone hennaing



(b) Temperature simulation result of continuous diffusion furnace with air curtain and heated by 3-zone hennaing



(c) Temperature simulation result of continuous diffusion furnace without air curtain and heated by 5-zone hennaing



(d) Temperature simulation result of continuous diffusion furnace with air curtain and heated by 5-zone hennaing

Figure 5: Temperature simulation results of continuous diffusion furnace in different conditions.

From the figure (a) and figure (b) we can see that when diffusion furnace is heated by 3-zone hennaing, if there is no air curtain, the temperature change in the furnace chamber like a parabola, which cannot meet basic requirement of diffusion; if adding air curtain, the relative temperature difference of the middle area of about 1m in the furnace chamber is small but not constant, so it cannot meet the basic needs of the diffusion. From the figure (c) and figure (d) we can see that when it is heated by 5-zone hennaing, if there is no air curtain, temperature difference exists in the middle area of about 1m in the furnace chamber is small but not constant, this situation cannot meet the basic needs of the diffusion; When adding air curtain at furnace mouth, the temperature of the middle area of about 1m in the furnace chamber is constant, so this case can meet basic needs of the diffusion.

4 TEMPERATURE CONTROL ALGORITHM DESIGN

The traditional PID control system can satisfy requirements of the system in most of cases because of its advantages that performance mature, easy to implement, eliminate the static error of advantages in most cases performance; but in process that control nonlinear, time variable, coupling and complex structure parameters, its effect is not very good. For this problem, this paper presents a PID cascade temperature control system based on Smith estimating pre-compensation compensation, the system can form cascade control by monitoring temperature of the furnace chamber and the furnace wall at the same time to meet performance requirements with small temperature overshoot, soon stabilization, high control precision.

4.1 Algorithm Design of the Control System

The purpose that design high precision temperature control system of diffusion furnace is mainly to ensure diffusion uniformity of the phosphorus element to silicon wafer. At present, main problems of the temperature control system of diffusion furnace is time of heat transfer process is too long from furnace wall to furnace chamber, for which we design a PID cascade control algorithm based on Smith estimating pre-compensation. Thought of Smith predictor is that regulated variable delayed is responded to controller in advance. Thought of cascade control is that adding a new control object - furnace wall temperature based on the original control object -furnace chamber temperature, it could response interference in advance; and increase the furnace wall temperature control can improve the quality of the whole control system. Cascade control system with Smith estimating pre-compensation as shown in Figure 6.

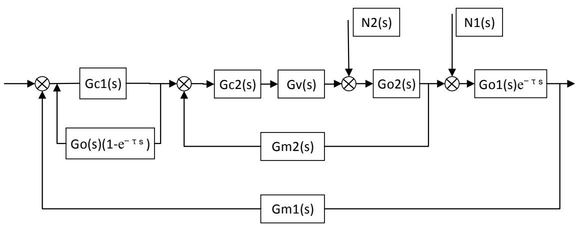


Figure 6: Transfer function schematic of cascade control system with Smith estimating pre-compensation.

In figure 6, Gc1(s) and Gc2(s) denote respectively the transfer functions of principal and subordinary regulators. Gv(s) denotes the transfer function of actuator; Go2 (s) denotes the transfer function of subloop controlled object; Go1(s)e-τs denotes the transfer function of t main loop controlled object; Gm1(s) and Gm2(s) denote respectively the transfer functions of main and auxiliary transmitter; Gv(s) denotes the transfer function of actuator; Go(s)(1-e-τs) is the Smith predictor of main loop.

In the Smith predictor:

$$G_O(\mathrm{s}) = \frac{G_m1(s)G_O1(s)G_C2(s)G_V(s)G_O2(s)}{1 + G_m1(s)G_C2(s)G_V(s)G_O2(s)} \quad (1)$$

The equivalent transfer function of the subloop is:

$$G_O2'(s) = \frac{Y_2(s)}{R_2(s)} = \frac{G_C2(s)G_V(s)G_O2(s)}{1 + G_m2(s)G_C(s)G_O2(s)G_V2(s)} \quad (2)$$

So, transfer function of cascade control system with Smith estimating pre-compensation is:

$$G(s) = \frac{Y(s)}{R_1(s)} = \frac{G_O(s)G_O2'(s)G_O1(s)}{1 + G_O(s)G_O2'(s)G_O1(s)G_m1(s)} e^{-\tau s} \quad (3)$$

The characteristic equation of the system can be seen from the above formula:

$$1 + G_O(s)G_O2'(s)G_{O1}(s)G_m1(s) = 0 \quad (4)$$

The characteristic equation does not contain $e^{-\tau s}$, so Smith predictor can make the temperature hysteresis quality does not affect the system.

4.2 System Simulation and Result Analysis

In this paper, the Simulink module of Matlab software is used to simulate the system control algorithm. In order to verify the control effect of cascade control method with Smith estimating pre-compensation, the conventional PID cascade control system is compared with it. The simulation model of the PID cascade control system with Smith estimating pre-compensation and the conventional PID cascade control system as shown in Figure 7.

The output response curve of the system under normal circumstances without interference as shown in Figure 8.

In the case of adding interference, for example, adding interference signal in the subloop when system stability time is 7000s. Set interference signal is the step signal, the output response curve of system as shown in figure 9.

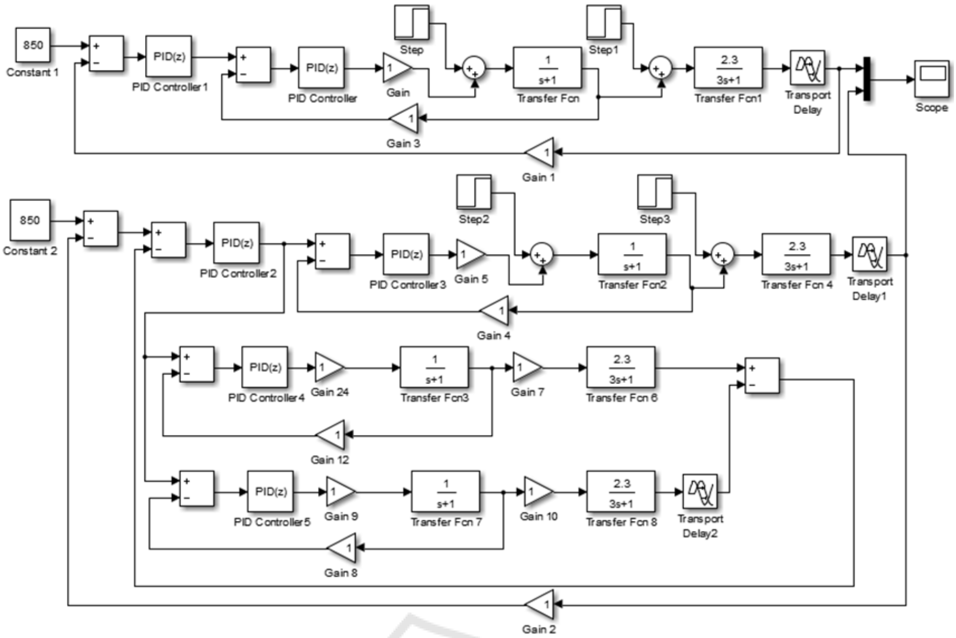


Figure 7: The simulation model of the PID cascade control system with Smith estimating pre-compensation.

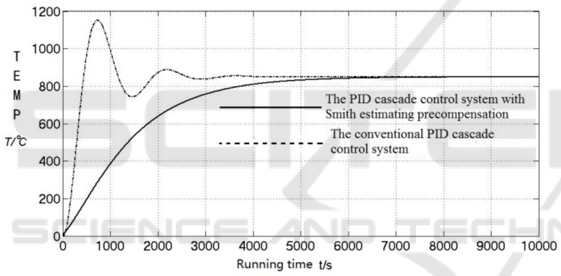


Figure 8: Output response curve of the system under normal circumstances.

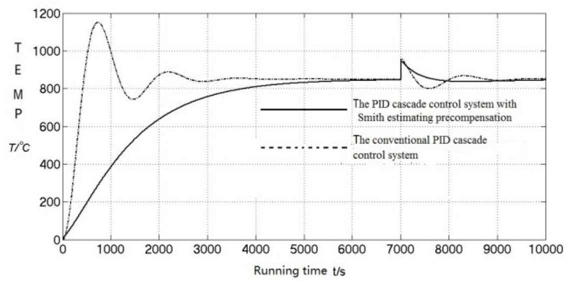


Figure 9: Output response curve of the system under adding interference.

As can be seen from figure 8, compared with the conventional PID cascade control system, the PID cascade control system with Smith predictor is more stable and no overshoots, thus it can protect the diffusion furnace and the control effect is better.

As can be seen from Figure 9, the PID cascade control system with Smith predictor is better in anti-interference ability than the conventional PID cascade control system.

To sum up we know, no matter in normal circumstances, or in the case of interference, the PID cascade control system with Smith estimating pre-compensation is better than the conventional PID cascade control system in control precision, stability and anti-interference ability.

5 EXPERIMENT

5.1 Temperature Control System Design of Continuous Diffusion Furnace

As shown in Figure 10, temperature control system is composed with temperature cascade control system and temperature overtemperature protection system. The principle of temperature cascade control system is that use subloop composed of the furnace wall outer thermocouple (A', B', C', D', E'), thermostat 2, trigger circuit, and power elements to control the heating current of furnace wire. And thermocouple (A, B, C, D, E) in the furnace chamber will measure temperature and compared with setting value, then together with thermostat 1, thermostat 2, triggering circuit and power elements compose main circuit to monitor furnace temperature of constant temperature area. The principle of overtemperature protection system is that overtemperature protection thermocouple, thermostat 3 (PLC), contactor KM1 compose control system, when the furnace temperature is higher than the maximum temperature that equipment can withstand in long time, the PLC (thermostat 3) output signal to make contactor KM1 power failure, and to stop heating furnace wire, at the same time PLC (thermostat 3) output signal to alarm indicator lamp to produce sound-light alarm.

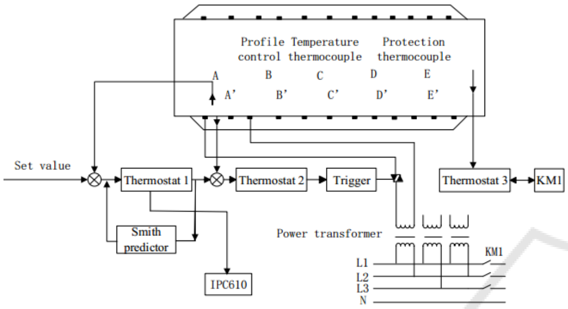


Figure 10: Temperature control system of Continuous diffusion furnace.

The interface of temperature control system is written by LabVIEW software, as shown in figure 11. The upper computer interface mainly composes display of real-time temperature, settings of parameters, establishment of the EXCEL table, etc.

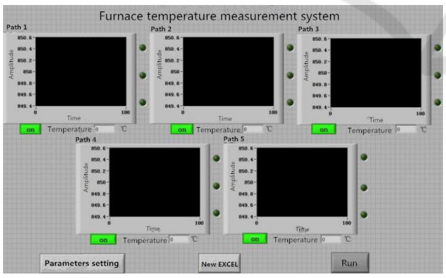


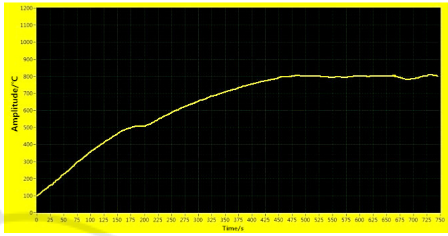
Figure 11: The interface of temperature control system.

5.2 Experimental Result Analysis of Continuous Diffusion Furnace

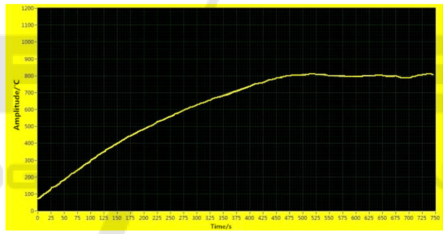
The prototype of the continuous diffusion furnace used in the experiment as shown in Figure 12, which including the control cabinet, gas source cabinet, purification cabinet, resistance heating furnace cabinet and so on.

Figure 12: The prototype of the continuous diffusion furnace.

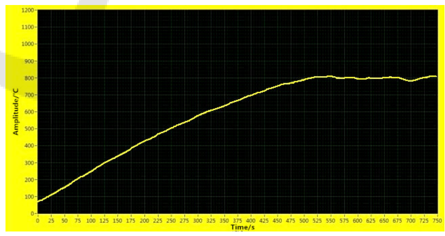
Using the LabVIEW record data of continuous diffusion furnace in heating process, as shown in Figure 13, (a), (b), (c), (d), (e) denote respectively the temperature heating curves of point A, B, C, D, E in figure 13.



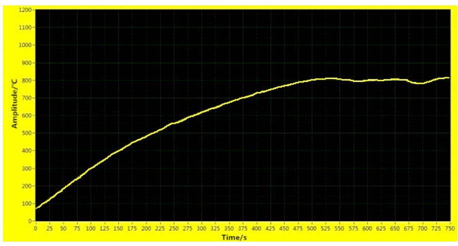
(a) The temperature heating curve of point A



(b) The temperature heating curve of point B

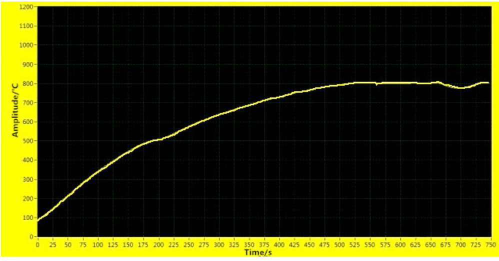


(c) The temperature heating curve of point C



(d) The temperature heating curve of point D

Figure 13: The actual furnace temperature curves of different position.



(e) The temperature heating curve of point E

Figure 13 (cont.): The actual furnace temperature curves of different position.

From the above temperature curves can be seen that heating process is roughly same in point A and point E, point B and D but there exists some difference among point A, B, C, D, E during heating process. The reasons that cause difference of temperature curves between A, E and B, C, D may be due to the influence of the air curtain at the furnace mouth, or caused duo to during heating process, first heating temperature to 500℃and then heating temperature 800℃. There is fluctuate after temperature stable at 800℃, the season is that paddle enter in furnace from the furnace door cause air fluctuation and then cause temperature fluctuation.

Compared temperature simulation curve of system shown in figure 9 with the actual temperature heating curves shown in figure 13, we can know that the heating rate and time that reach to stable temperature both are roughly same. In the case of external interference, the system can restore to a stable state effectively.

6 CONCLUSIONS

In this paper, the temperature of continuous diffusion furnace is the research object. Aim at the temperature control characteristics of diffusion furnace with large inertia and pure hysteresis, this paper proposes a furnace temperature control system with PID cascade control algorithm based on Smith prediction compensation. Through the simulation analysis and actual experiments of furnace temperature control system, the paper verifies the effectiveness of the control algorithm and the effectiveness of the furnace temperature control system.

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