Research of Multi-Point Temperature Control Method in the Heating System of 3D Glass Hot Bending Machine

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Abstract. 3D glass hot bending machine is widely used to produce 3D glass. The heating system is its one of key components. The uniformity of surface temperature distribution of the heating plate in the heating system decides the quality of 3D glass products. At present, the heating system of 3D glass hot bending machine mainly uses single-point temperature control method to adjust the system temperature. However, the single-point temperature control method cannot guarantee the uniformity of surface temperature distribution of the heating plate. In this research, multi-point temperature control method was proposed and the simulation model was established by ABAQUS. The control effect of single-point control method and multi-point temperature control method were compared through simulations and experiments. The results show that the multi-point temperature control method can reduce the surface temperature difference of the heating plate and achieve temperature uniformity so as to improve the quality of 3D glass products.

1. Introduction
The advent of 5G era has brought new opportunities and challenges to the smartphone-related market. The increase of signal transmission rate makes higher requirements to the hardware. The traditional metal mobile phone cover has a certain shielding effect on the signal, which cannot meet the requirements of 5G signal transmission rate. 3D glass as a kind of non-metallic materials has been widely used in the smartphones due to its non-shielding effect on the signal, beautiful looking and comfortable feeling, etc.

In the manufacturing of 3D glass, a piece of flat glass is required to pass through several processing steps, such as cutting, hot bending, polishing, printing, fitting and inspection, to finally become a piece of qualified 3D glass. One of the most important steps which affects the yield and quality of 3D glass is hot bending. Figure 1 shows the 3D glass hot bending machine. There are four steps in hot bending, that is heating, forming, annealing and cooling [1-2]. The temperature of the heating system is gradually raised above the transition temperature of the glass, and a certain pressure is applied on the glass to shape the glass to the mould structure.

Temperature control is extremely important in the hot bending process. The heating plate heats the mould by means of heat conduction [3]. If the surface temperature of the heating plate is not uniform enough, additional thermal stress will be generated in the glass, which will affect the quality of the 3D glass products [4]. Poor heating effect also wastes heat and increases energy consumption. Therefore, the heating system of 3D glass hot bending machine need be analysed and the more reasonable temperature control method need be applied.
Transient thermal simulation technology is a good way to predict temperature changes. Chang [5] built a simulation model to analyse the surface temperature based on ANSYS. Proportional integral derivative (PID) control method is a reliable control method, which has been applied in many fields [6], especially in temperature control [7]. The heating furnace temperature was controlled based on the expert fuzzy PID method and it was proved the method was effective [8]. Using self-tuning-parameter fuzzy PID controller, Feng [9] researched the temperature control of a large hydraulic system. Punse [10] designed a multi-point temperature control method based on self-tuning PID and proved its feasibility in temperature control of heaters.

At present, 3D glass hot bending machine usually adopts single-point temperature control method to control the surface temperature of the heating plate. All heating rods can only be controlled according to the temperature measured by the thermocouple in the middle of the heating plate, which leads to the temperature distribution on the surface of the heating plate cannot realize uniform. However, there is fewer researches which improves the temperature control effect of 3D glass hot bending machine.

In this research, the temperature control technology of the 3D glass hot bending machine was analysed. Multi-point temperature control method was proposed. The control effects of both single-point temperature control method and multi-point temperature control method were compared. Simulation and experimental analysis of the two methods were carried out respectively.

![Figure 1. Schematic diagram of 3D glass hot bending machine.](image)

2. Heating system of 3D glass hot bending machine

2.1. Heating system composition

![Figure 2. Heating system of 3D glass hot bending machine.](image)

The heating plate is in direct contacting with the mould. During the glass hot bending process, the mould is heated by the heating plate through heat conduction. A heating system is required to control
the temperature of the heating plate to reach the preset temperature. The heating system of 3D hot bending machine is mainly composed of thermocouple, temperature controller, power regulator, heating rods and heating plate. The heating system of 3D glass hot bending machine is shown in figure 2.

As a temperature measuring equipment, thermocouple is responsible for transferring the measured temperature to the temperature controller. According to the preset temperature and the actual measured temperature, the temperature controller outputs a control signal to the power regulator. The heating rod is the ultimate actuator, which converting electrical energy into heat on the basis of the power regulator.

2.2. Principle of temperature control

Temperature control is the most important part in the heating system of 3D glass hot bending machine, which relates to whether the heating plate can successfully reach the preset temperature and maintain the uniform temperature distribution. The surface temperature of the heating plate is controlled by the temperature controller according to the temperature measured by the thermocouple and the preset temperature. Temperature control is mainly achieved by the PID program inside the temperature controller. PID is a kind of control method, which is fully called proportional integral derivative control. PID control method is composed of three parts, that is the proportion, integral and differential of deviations. These three parts are combined together to carry out the negative feedback control for the controlled object to enable it to remain the preset value. PID control rule can be expressed by formula (1).

\[ u(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{de(t)}{dt} \]  

(1)

Where, \( e(t) \) is the deviation between the preset value and the measured value, and \( u(t) \) is the input value of the controlled object. It is a function value generated on the deviation value \( e(t) \) according to PID control method [11]. \( K_p \) is the proportionality coefficient. The greater the deviation between the measured temperature and the preset temperature is, the greater the input power is. There is no input value if there is no deviation value. This is not a stable state. The measured temperature cannot be stable and can only fluctuate within a range of the preset temperature. Therefore, only relying on proportional control to adjust can produce a fluctuation, which is not conducive to the control of temperature accuracy. \( K_i \) is the integral coefficient. The purpose of introducing integral regulation is to eliminate the steady state error of proportional control. As time goes on, the integral of the temperature difference increases until the difference disappears so that stability is achieved. \( K_d \) is the differential coefficient. The function of differential regulation is to find error in advance and avoid it to improve system response speed.

2.3. Multi-point temperature control design

At present, the single-point control method is widely used in 3D glass hot bending machine. That is to say, all the heating rods are simultaneously controlled by one temperature controller. If the temperature measured by the central thermocouple is too high, the temperature controller will decrease the power of all heating rods. Uneven temperature distribution will appear on the surface of the heating plate.

In order to improve the temperature control effect, a multi-point temperature control method was designed. Three thermocouples were installed on the heating plate. Each thermocouple was paired with a temperature controller and a power regulator. Each temperature controller controlled two heating rods which were located symmetrically along the center of the heating plate. The temperature controller can control the two heating rods according to the power regulator to heat the plate.
3. Simulation analysis of heating plate temperature control

3.1. Simulation settings
In this research, the temperature control on the surface of the heating plate was mainly analyzed. Without taking the temperature change in the direction of length into account, a 2D model was built. The material parameters of the heating plate are shown in Table 1. Transient thermal simulation was used to analyze the temperature change. The heating input of the heating plate was to convert the actual heating power into heat flux. The bottom surface of the heating plate is connected to the insulation plate. The heat transfer was ignored, and the bottom surface was considered as adiabatic. Other surfaces were set to exchange heat by means of air convection heat transfer. Three observation points were set on the surface of the heating plate to record the surface temperature of the heating plate. The simulation model is shown in Figure 3.

![Diagram](image)

Figure 3. 2D simulation model of the heating plate.

| Density (kg/m³) | Conductivity (W/m²·°C) | Specific Heat Capacity (J/(kg·°C)) |
|----------------|-------------------------|----------------------------------|
| 7980           | 16.5(100°C)             | 21.3(500°C)                      |
|                | 500                     |

In order to realize the negative feedback control of the surface temperature of the heating plate, the subroutine of ABAQUS needs to be introduced. There are various subroutines in ABAQUS, which can expand the functions of ABAQUS and make the simulation more in line with the actual process [12]. User-defined amplitude (UAMP) is an amplitude subroutine that controls the amplitude of the input. The following was the process of temperature control through UAMP. Firstly, H_SENSOR was set as a detector to observe the surface temperature of the heating plate which was similar to the function of a thermocouple. PID control method was used to determine an output coefficient according to the preset temperature and the measured temperature in H_SENSOR to adjust the loading amplitude. The specific values of PID were determined according to the actual values used by the temperature controller. The single-point temperature control method only needed set one H_SENSOR as the detector. The six heating rods load were adjusted according to the subroutine. In the multi-point temperature control method, three H_SENSORs were set, which transferred the measured temperatures to three subroutines to obtain three amplitude coefficients, and adjusted the power of the three pair of heating rods respectively.

3.2. Simulation results
The simulation analysis of single-point control method and multi-point temperature control method was carried out respectively. When the temperature of observation point 1 reached the range of ±5°C of the preset temperature, the temperature results would be output. Figure 4 shows a comparison of surface temperature of the heating plate of two temperature control methods. The temperature distribution on the surface of the heating plate was more even when using three-point temperature control method.

Figure 5 and figure 6 are the images of temperature change with time obtained by two temperature control methods. Temperature control came into play after the temperature of the observation point
was near the preset temperature. It could be seen that the temperature at observation point 3 obviously fluctuates in the situation of the single-point temperature control method. The minimum value was already about 13.1°C less than the preset temperature. In the case of multi-point temperature control method, the temperature of the three observation points could be maintained near the preset temperature with a small deviation value.

![Temperature distribution in the heating plate based on simulation results.](image)

**Figure 4.** Temperature distribution in the heating plate based on simulation results.

![Temperature - time diagram based on simulation results of single-point temperature control method.](image)

**Figure 5.** The temperature - time diagram based on simulation results of single-point temperature control method.

![Temperature - time diagram based on simulation results of multi-point temperature control method.](image)

**Figure 6.** The temperature - time diagram based on simulation results of multi-point temperature control method.

### 4. Temperature control experiment of heating plate

#### 4.1. Experimental facilities

According to the heating system of the 3D glass hot bending machine, a temperature control experimental platform was built, which is shown in figure 7. The multiplex temperature recorder and PC were mainly used to record the temperature change of the heating plate.

![The physical picture of the temperature control experiment platform.](image)

**Figure 7.** The physical picture of the temperature control experiment platform.
For single-point temperature control method, there was only one thermocouple, temperature controller, and power regulator. For multi-point temperature control method, three thermocouples, temperature controllers and power regulators were used. The experiments could be carried out on this platform. When the central point reached ±5°C of the preset temperature, the data would be recorded.

4.2. Temperature control experiments

The single-point and multi-point temperature control experiments of the heating plate were carried out on the experimental platform.

In the single point temperature control experiment, with the increase of time, the temperature of three observation points showed great fluctuations, as shown in figure 8. At the observation point 3, there was a difference less than the preset temperature of 12.3°C. The main reason for this situation was that in the single-point temperature control method, the temperature adjustment to the 6 heating rods was synchronous. When the temperature on both sides of the heating plate was low, however the temperature measured by the thermocouple was near the preset temperature. Thus the power of the heating rod had could not be increased to heat up the sides of the heating plate.

In the three-point temperature control experiment, three loading coefficients could be obtained according to three thermocouples, which could directly regulate and control the heating rod near the thermocouple to reduce temperature fluctuation. In figure 9, the temperature at three points is maintained within ±3°C of the preset temperature after 200s.

By comparing the simulation results with the experimental results, it was found that the simulation results were basically consistent with the actual results. And it could be proved that multi-point control method was more suitable to achieve the uniformity of surface temperature distribution of the heating plate in the heating system of 3D glass hot bending machine.

5. Conclusions

In this research, the temperature control process of the heating plate was simulated and analysed. An experimental platform was built to analyse the single-point and multi-point temperature control experiments of the heating plate in the heating system of 3D glass hot bending machine. According to the research results, the following conclusions could be drawn:

1) Single-point temperature control method could cause uneven temperature distribution on the surface of the heating plate. There would be a difference of 12.3°C on the surface of the heating plate, which was detrimental to the quality of the 3D glass products.

2) Multi-point temperature control method could effectively avoid the expansion of temperature difference. The temperature measuring points could be maintained within ±3°C around the preset temperature.
3) Through the simulation and experimental analysis of the heating plate, it could be found that the simulation can well predict the experimental results. Multi-point temperature control method was more suitable to achieve the uniformity of surface temperature distribution. This method will be beneficial to improve the quality of 3D glass products.

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