Research on Temperature Control Technology of Thermal Protection Device for The Low Temperature Wind Tunnel Equipment

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Abstract. One of the important technologies to improve the Reynolds number is to reduce the temperature of the air flow inside the wind tunnel. The air flow working temperature can reach 77K at least. At this time, it is necessary to carry out thermal protection for the internal equipment of the wind tunnel. In view of the complex layout and various characteristics of the equipment in the wind tunnel, this paper takes the thermal protection and temperature control strategy of the equipment in the wind tunnel as the research object, and designs the temperature control strategy of the typical equipment from the perspectives of heating element selection, temperature control logic, temperature control algorithm and heating mode. A physical test platform was designed and built. The feasibility of temperature control strategy was verified by the physical test platform under two typical temperature conditions of normal temperature and low temperature. The test results show that the comprehensive design of the temperature control strategy can meet the temperature control requirements of different shapes, heat capacities and heat leakage conditions, and the temperature control accuracy is better than 1 °C, which can meet the design requirements and effectively ensure the normal operation of the equipment in the wind tunnel.

1. Introduction
When the low-temperature wind tunnel is running, the air flow temperature in it can reach 77K at least, which is far lower than the normal working temperature of some kinds of mechanical, electrical and electronic equipment. Therefore, it is necessary to carry out thermal protection for its internal equipment to ensure that it is in the normal working temperature range.

In view of the wide variety of internal equipment and complex layout of a wind tunnel, in order to achieve effective thermal protection for the internal equipment of a wind tunnel, the multilayer thermal insulation modules and PIR insulation foam are used for passive thermal protection, active heating protection is needed for heating equipment. In this paper, the temperature control strategy of active thermal protection for different shapes, heat capacity and heat leakage conditions in wind tunnel was studied. The temperature control strategy of typical equipment was designed synthetically from the perspectives of heating element selection, temperature control algorithm, temperature control logic and heating mode. The physical verification platform of temperature control strategy is designed based on PLC system. The temperature control strategy is tested and analyzed under different operating conditions.
conditions, which provides theoretical and engineering data support for the design of the internal equipment safety protection system of a wind tunnel.

2. Design of temperature control strategy for equipment in wind tunnel

The equipments that need active thermal protection in wind tunnel mainly include mechanical, electrical, electronic and other kinds of equipments, which have various types and different specifications. In order to facilitate the unified design of equipment active thermal protection and temperature control system and temperature control strategy, the temperature control objects were abstractly classified into two typical structures: plane and solid. The temperature control system was designed based on the PLC system, which includes the PLC control system, the distributed I/O system, power supply, and the temperature measurement and heating elements at the specific protected equipment unit. The design can realize the closed-loop control of hundreds of equipment units in the wind tunnel on the basis of clear structure, good reliability and high integration. The design principle of the equipment temperature control system in the wind tunnel is shown in Figure 1.

![Figure 1. Design principle of thermal protection and temperature control system in wind tunnel](image)

The principle of thermal protection and temperature control for different types of temperature control objects is basically the same, as shown in Figure 1. However, due to the different area, volume, heat capacity and location of different temperature control objects, the temperature control strategies of different temperature control objects need to be designed comprehensively to meet their temperature control needs.

The temperature control strategies are mainly compared, analyzed and designed from the aspects of heating element selection, temperature control logic, temperature control algorithm and heating mode, among which:

1) In order to realize the effective heating of the object with plane and solid shape temperature control, membrane heater and heating rod are used to heat the object respectively.

2) Due to the different volume sizes of temperature control objects, in order to ensure the uniformity of temperature control, the control strategy should be designed from the perspective of temperature control logic. For equipment with larger volume and heat capacity, many-to-many individual temperature control logic can be selected, that is, multiple temperature control elements correspond to multiple temperature measurement points, which are independent of each other. On the contrary, for equipment with smaller volume and heat capacity, an unified temperature control logic is recommended to eliminate the mutual interference caused by temperature control alone between multiple heating elements.

3) The two temperature control algorithms, switch control and PID control, are analyzed and compared. Among them, the logic of switch control algorithm is simpler, easier to realize, and the speed of temperature control is faster. However, in terms of temperature control accuracy, especially for large heat capacity objects, PID temperature control algorithm can reduce overshoot and improve temperature control accuracy by adjusting P, I and D parameters.

4) Heating mode refers to the power supply mode of heating elements, which is the final means to achieve temperature control, generally includes power regulation control and constant power.
intermittent control. Among them, power regulation control is continuous power output, mainly through the large and small adjustment of output current or voltage, to achieve the regulation of power supply of heating elements, with high control accuracy; constant power intermittent control By controlling the duty cycle of constant power output, the power supply of heating elements can be adjusted, and the temperature control speed is faster. The choice of heating mode is directly related to the choice of power supply of the control system, which needs to be comprehensively considered from the perspective of control effect, cost, implementation difficulty, etc.

3. Design of temperature control strategy test platform

In order to realize the physical verification and analysis of the temperature control strategy of the equipment in the wind tunnel, this paper designs and builds a temperature control test platform based on PLC technology. The system follows the principle of minimization, modularization and expansibility, and can realize the physical test verification of the typical temperature control objects and their multiple temperature control strategies.

As shown in Figure 2, the platform system is mainly composed of S7-300 PLC upper computer control unit, AI / AO / DO modules, solid-state relay, power module, heating elements such as film heater and heating rod, temperature transmitter, and hardware such as temperature measurement platinum resistance and upper computer control software. The upper computer control software is developed based on LabVIEW, and the software interface is shown in Figure 3.
The power supply unit composed of DO output module, solid-state relay and DC-DC power supply in the platform system that is used for the simulation of constant power intermittent control heating mode by controls the opening and closing of DC power output through solid-state relay. The power supply unit composed of AO and program-controlled power supply that is used for the model of power regulation control heating mode by controls the output current of program-controlled power supply through AO output analog quantity.

Copper square plate and cylinder are respectively used for physical simulation of temperature control objects of typical specifications such as plane and solid shape. Due to the shape limitation of square plate, only thin film heating plate can be used as heating element, while thin film heating plate and heating rod are used for cylinder. The armored platinum resistance is used for temperature measurement element. The implementation method of copper plate and cylinder heating and temperature measurement element is shown in Table 1, where one heating piece corresponds to one platinum resistance, and 3 heating rods corresponds to one platinum resistance.

| Temperature control object | number | heating element | temperature measurement element |
|---------------------------|--------|-----------------|---------------------------------|
| Square plate              | 1      | 2 heating plate | 2 platinum resistance           |
| Cylinder                  | 2      | 1 heating plate | 1 platinum resistance           |
| Cylinder                  | 1      | 6 heating rod   | 2 platinum resistance           |

4. Test verification and result analysis

In order to fully compare and verify the feasibility of the temperature control strategy of wind tunnel equipment thermal protection, this paper uses the temperature control strategy test platform, combined with the low-temperature test chamber, and designs the corresponding test conditions under the two environmental conditions of normal temperature and low temperature. Then, the test verification and result analysis of the temperature control strategy were carried out from the perspective of temperature control logic, temperature control algorithm and heating model.

Figure 4. Temperature control strategy verification test site

4.1. Analysis of temperature control logic test

The comparative analysis of temperature control logic mainly takes the uniformity of temperature control of equipment as the research object, and tests and analyzes two corresponding logics of "unified" and "separate" of equipment heating and temperature measuring elements. The design of this part of test conditions is shown in Table 2, in which “unified” mode, 1# platinum resistance on each temperature control object is selected as the temperature feedback of closed-loop control.

| Condition No | Control object | Control logic | Control temperature |
|--------------|----------------|---------------|---------------------|
| Condition 1  | Square plate   | Separate      | 40°C                |
| Condition 2  | Square plate   | Unified       | 40°C                |
| Condition 3  | Cylinder(heating rod) | Separate     | 40°C                |
| Condition 4  | Cylinder(heating rod) | Unified      | 40°C                |
The condition 1~4 is the normal temperature environment, and the square plate and cylinder (heating rod) are tested under different temperature control logic conditions. During the final temperature control value of 40°C, 30°C step is set to realize the repeatability verification of temperature control effect. The temperature control effect curves are shown in Figure 5 and Figure 6 respectively.

It can be seen from Figure 5 that the two kinds of temperature control logic are used to control the temperature on the opposite board. When the “unified” temperature control logic is used, the temperature difference between the two temperature measurement points is relatively small, which basically within 0.5°C, and there is no obvious temperature control interference phenomenon, and the temperature uniformity is better.

![Figure 5. Different temperature control logic temperature error curve of square plate](image)

![Figure 6. Different temperature control logic temperature error curve of cylinder](image)

It can be seen from Figure 6 that when the “unified” temperature control logic is used, the maximum temperature difference between the two points is 0.53 °C. When the “separate” temperature control logic is used to control the temperature of the cylinder, the maximum temperature difference between the two points is 0.28°C in the temperature stable section. Therefore, the “separate” is more suitable to the control object with large volume and large heat capacity, the complicated heat conduction relationship and large thermal resistance, and ensure its uniformity and accuracy of thermal protection.
4.2. Analysis of temperature control algorithm test

The comparative analysis of temperature control algorithm is mainly carried out for two temperature control algorithms, switch control and PID control. The design of test conditions is shown in Table 3.

| Condition No | Environment condition          | Square plate Control temperature | Cylinder (heating rod) Control temperature |
|--------------|--------------------------------|----------------------------------|------------------------------------------|
| Condition 5  | Normal temperature and pressure| Switch control                   | PID control                               | 40°C                                    |
| Condition 6  |                                |                                  | PID control                               | Switch control                          |                                    |
| Condition 7  | Low temperature and normal pressure | Switch control                  | PID control                               | -35°C                                   |
| Condition 8  |                                |                                  | PID control                               | Switch control                          |                                    |

The conditions 5 and 6 are normal temperature and pressure conditions. The temperature control objects of square plate and cylinder are respectively controlled by switch control and PID control algorithm at 40°C, and the temperature control data of working conditions are shown in Figure 7.

![Temperature curves](image)

It can be seen from Figure 7 that in the temperature rise stage from normal temperature to 40°C under working conditions 5 and 6, due to the cylinder’s large heat capacity of body structure, its temperature control hysteresis is strong, the temperature rise time is longer, and the control overshoot is large. For any temperature control object, the maximum temperature overshoot of PID control algorithm is less than 2°C, which is better than that of switch control algorithm, and the overshoot can be further reduced to a smaller value by adjusting PID parameters.

In addition, in the temperature stable section of condition 5 and 6, the maximum temperature control error of PID algorithm for any temperature control object is less than 0.6°C, and in the convergence trend, which is better than the switch control algorithm. While the temperature of the control object controlled by the switch algorithm presents different frequency and amplitude oscillations, especially for the cylinder with large heat capacity, the maximum temperature difference controlled by the switch is greater than 1°C.

Under the condition of low temperature and normal pressure, two temperature control algorithms are adopted for the temperature control object of the square plate and cylinder respectively, and the temperature control target temperature is set in two stages of -45°C and -35°C. The temperature control data curve is shown in Figure 8.
4.3. Analysis of heating mode test

In order to compare and analyze the temperature control performance differences between the two heating modes of power regulation control and constant power intermittent control, the two heating modes are respectively used to control the temperature of the heating circuit 1 and heating circuit 2 of the square plate analog, and the temperature control steps are set at 45 °C and 50 °C. The temperature control effect curve is shown in Figure 9.

![Figure 9. Heating mode verification test temperature control effect curve](image-url)

It can be seen from Figure 11 that the two heating modes meet the requirements of temperature control and the difference is small. In comparison, in the heating stage, the overshoot and time coefficient of constant power intermittent control are small, while in the temperature stability stage, the temperature difference of power regulation control is small and the accuracy is slightly better. Considering the large number of internal equipment in a wind tunnel, from the point of view of temperature control performance and engineering complexity, constant power intermittent control mode is adopted, that is, the mode of heating element power supply through constant voltage bus and solid-state relay, with better comprehensive efficiency.

Acknowledgments

This paper takes the thermal protection of the equipment in the wind tunnel as the research object, designs the temperature control strategy of the typical equipment model, makes theoretical comparison
and analysis of the algorithm from the angles of heating elements, temperature control algorithm, temperature control logic and heating mode. The hardware and software test platform for the verification of the temperature control strategy was developed. The test conditions from different angles of the temperature control strategy were designed and implemented. The test results fully prove the correctness and feasibility of the temperature control strategy design, and provide an effective theoretical and data support for the engineering realization of thermal protection of equipment in a wind tunnel.

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