Research and Implementation of Temperature Control Method for Large Space Climatic Laboratory

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Abstract. The temperature control of aircraft climatic laboratory has the feature of big time delay, large temperature range and non-linear. A temperature control method of feedforward-cascade PID is proposed. Firstly, the model for temperature change of climatic laboratory is established through mechanism analysis, and the parameters of model are obtained based on step response curve identification method; Secondly, on the basis of analyzing the dynamic characteristics of the temperature control system, a two-stage refrigerant temperature control strategy based on constant flow and variable temperature is proposed, and a feedforward-cascade PID controller is designed; Finally, the controller parameters are obtained by the critical proportion method and trial-and-error method, then the controller is applied to the temperature control of the climatic laboratory. The results show that the control method can improve the dynamic response of the system and accurately track the desired temperature curve. This method has the advantages of fast response, no overshoot, high steady-state precision, and achieves the expected goal of temperature control.

Keywords: Climatic laboratory · Temperature control · Large time delay · Feed-forward control · Cascade PID

1 Introduction

In order to meet the experimental needs of aviation, aerospace and other industries for the products' climate adaptability, China has established a super large space climatic laboratory to realize the test for large-scale test pieces such as aircraft and vehicles. The climate laboratory can simulate various climatic environments which can help engineers obtain the function and performance data by putting the products in the laboratory. These data can expose the products' design or process defects, and provide the basis for improving the design of products' climate adaptability [1–4]. Temperature test is the most important test in products' climatic environment test. The national military standard proposes strict requirements for temperature regulation rate, stability and other indicators in the temperature control process. The temperature must be accurately controlled to ensure the authenticity of test data.

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The climatic laboratory has a large space and a wide range of temperature, so the temperature control has the characteristics of large time delay and nonlinearity. The test piece, auxiliary equipment, lights and floor will bring heat load interference to the temperature control process. It is difficult to achieve good dynamic and steady state characteristics at the same time by using the classical PID control method [5]. In order to solve the above problems, the paper analyzes the dynamic characteristics of temperature control process, and the transfer function is obtained by the step response identify method. A feedforward cascade PID temperature control method is proposed and applied to the climatic laboratory. This method makes the temperature rise-fall rate and steady-state fluctuation meet the requirements, and it achieves the goal of accurate temperature control.

2 Temperature Control System Model of Climatic Laboratory

2.1 The Composition of Temperature Control System

Super large space climatic laboratory is often used for temperature test of aircraft, automobile and other products. According to the temperature extreme values recorded in GJB 1172.2 “extreme climatic values of military equipment” and the actual measurement results of the temperature when the aircraft is parked at the airport, the low temperature extreme value experienced by the aircraft during operation and storage is −55°C and the high temperature extreme value is + 71 °C [6]. In order to cover the extreme temperature, the temperature regulation range of the climate laboratory is −55°C ~ + 71 °C. The temperature change rate during the heating or cooling process in the laboratory is less than 3°C/h, and the temperature control accuracy is ±3 °C. Temperature environment simulation equipment includes centrifugal fan, high-temperature heat exchanger, low-temperature heat exchanger, refrigeration unit and steam heat exchanger. The schematic diagram of temperature control process for climatic laboratory is shown in Fig. 1.

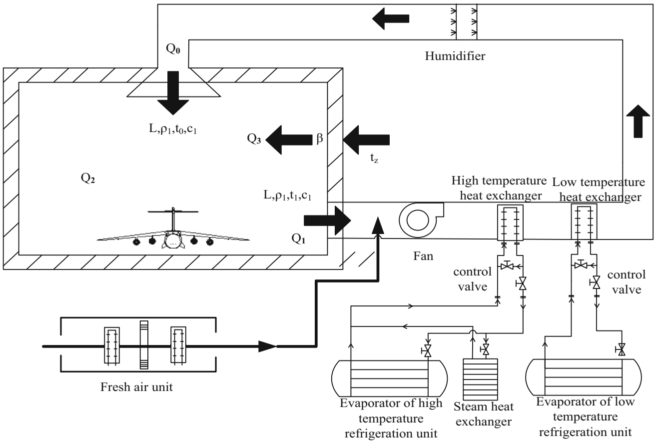

Fig. 1. The schematic diagram of temperature control process for climatic laboratory

The climatic laboratory adopts the air distribution form of top-air supply and side-air return. The air inside the laboratory enters the air-handling-unit from the return air outlet for temperature regulation, and then is sent to the laboratory from the top air outlet. After the air temperature in the laboratory achieves the expected value, the temperature test can start[7, 8]. In order to realize the wide temperature range (−55 °C ~ + 74 °C) regulation of the laboratory, two-stage heat exchangers with different refrigerant are arranged in the air-handling-unit to realize different temperature control. The first stage heat exchanger with high temperature refrigerant is used to realize the temperature regulation of −25 °C ~ + 71 °C. The cold source used in the temperature range of −25 °C ~ + 20 °C is the R507 high-temperature refrigeration unit, and the steam is used for heat source in the temperature range of + 20 °C ~+ 71 °C. The second stage heat exchanger with low temperature refrigerant is used to realize the temperature regulation of −55°C ~ +25°C and the cold source used in the temperature range is R23 low-temperature refrigeration unit. The two-stage heat exchangers are parallel arranged in the air-handling-unit [9]. The refrigerant pipeline of the two-stage heat exchanger is equipped with defrosting electric heating, which can also be used as the heat source in the heating process.

2.2 Modeling of Temperature Control System

The temperature changes of the climatic laboratory are closely related to the heat source, the enclosure structure, outdoor temperature, the indoor working equipment, etc. According to the principle of conservation of energy, the energy gradient of the laboratory is equal to the entering energy minus the outflow energy within unit time. The entering energy includes the heat emitted from working equipment in the laboratory(Q_2), the heat from air inlet(Q_0) and the heat transmitted from the outside of the laboratory(Q_3). The outflow energy is air flowing through the air outlet(Q_1). It can assume that the heat capacity of the laboratory is C_1 and the temperature is t_1, so the energy gradient can be expressed as follow:

$$C_1\frac{dt_1}{d\tau} = Q_0 + Q_2 + Q_3 - Q_1 \tag{1}$$

Assuming that: the supply air density is ρ_1; the supply air volume is L; air specific heat is C_0; the supply air temperature is t_0; the laboratory wall's thermal resistance is R; outside temperature is t_z; the enclosure structure's heat transfer attenuation coefficient is β.

Equation (1) can be expressed as

$$C_1\frac{dt_1}{d\tau} = L\rho_1 c_0(t_0 - t_1) + Q_2 + \frac{1}{R}\beta(t_z - t_1) \tag{2}$$

Transposing the formula (2),

$$\frac{C_1}{L\rho_1 c_0 + \frac{1}{R}\beta}\frac{dt_1}{d\tau} + t_1 = \frac{L\rho_1 c_0}{L\rho_1 c_0 + \frac{1}{R}\beta}t_0 + \frac{Q_2 + \frac{1}{R}\beta t_z}{L\rho_1 c_0 + \frac{1}{R}\beta} \tag{3}$$

Assuming that:

$$T = \frac{C_1}{L\rho_1 c_0 + \frac{1}{R}\beta}, K = \frac{L\rho_1 c_0}{L\rho_1 c_0 + \frac{1}{R}\beta} \tag{4}$$

$$t_f = t_{f1} + t_{f1} = \frac{Q_2}{L\rho_1 c_0} + \frac{1}{L\rho_1 c_0} \cdot \frac{\beta t_z}{R} \tag{5}$$

The formula (3) can be expressed as

$$T\frac{dt_1}{d\tau} + t_1 = K\big(t_0 + t_f\big) \tag{6}$$

In Eq. (6), t_0 is the control variable while t_{f} is the interference variable, and t_1 is the controlled variable.

Assuming the input is a time function and the laboratory's delay-time is τ_1, Eq. (6) can be expressed as

$$T\frac{dt_1(\tau)}{d\tau} + t_1(\tau) = K[t_0(\tau - \tau_1) + t_f(\tau - \tau_1)] \tag{7}$$

Assuming the initial condition is zero, the laplace transformation of Eq. (7) is

$$G(s) = \frac{T_1(s)}{T_0(s) + T_f(s)} = \frac{K}{Ts + 1}e^{-\tau_1 s} \tag{8}$$

Therefore, the climatic laboratory's temperature control process can be expressed as a first-order inertial system with delay component.

2.3 Identification of the Model Parameters

The main purpose of establishing the system model is to design the controller and evaluate the dynamic and static characteristics and control strategy of the system, while the acquisition of the system model requires parameter identification. In order to improve the fitting degree of the model, the model obtained by system identification is usually a high-order model, while the commonly used Ziegler Nichols PID controller tuning method is based on the low-order model. As we all know, by adjusting the parameters of the low-order model to change the shape of the step response curve, we can constantly approach the step response curve of the high-order system. As long as the fitting degree of the step response curve between the identification model and the original system is well enough, the identification model can reflect the original system's characteristics [10]. Therefore, the system model can be obtained by step response identification method.

The aircraft climatic laboratory's temperature control process can be expressed as formula (8). The gain K affects the steady-state response value; the constant T affects the step response speed; the delay time of the system is τ_1. In order to obtain the temperature step response curve of the climatic laboratory, start the high-temperature refrigeration unit, adjust the refrigerant to—10 °C, fully open the refrigerant regulating valve of the heat exchanger, and then start the fan at the normal operating frequency of 30 Hz. After the laboratory temperature reaches the stable state, the temperature step response curve of the climate laboratory is obtained. On the step response curve, the corresponding time when the temperature reaches to 95% of the final value is the adjustment time T_{s}, and the time constant T is 1/3 of T_{s}; the steady-state value of the step response curve is K; the time from the start of fan operation to the start of temperature drop is the delay time.

From the step response curve, the temperature control process model of the climatic laboratory is

$$G(s) = \frac{0.72}{688s + 1}e^{-90s} \tag{9}$$

3 Designation of Temperature Control System

3.1 Control Strategy

According to the schematic diagram of temperature control for climatic laboratory, the temperature control strategies are as follow:

(1) Reduce the laboratory's temperature from room temperature (generally +20 °C) to [−25 °C, + 20 °C]: the cold source is the R507 high-temperature refrigeration unit, and the first stage heat exchanger works.
(2) Reduce the laboratory's temperature from −25 °C to [−55 °C, −25 °C): the cold source is the R23 low-temperature refrigeration unit,and the second stage heat exchanger works.
(3) Raise the laboratory's temperature from −55 °C to (−55 °C, −25 °C]: the heat source is the electric heater,and the second stage heat exchanger works.
(4) Raise the laboratory's temperature from -25°C to (−25 °C, + 20 °C]: the heat source is the electric heater, and the first stage heat exchanger works.
(5) Raise the laboratory's temperature from + 20°C to (+20 °C, +71 °C]: the heat source is steam, and the first stage heat exchanger works.
(6) Reduce the laboratory's temperature from +71 °C to [+20 °C, +71 °C): the cold source is R507 high-temperature refrigeration unit, and the first stage heat exchanger works.

According to the above control strategies, the temperature of the refrigerant needs to be adjusted first in the temperature control process. In the primary refrigerant circulation system, the refrigerant is cooled by refrigeration unit and is heated by steam. The process schematic diagram of the refrigerant temperature control in the secondary refrigerant circulation system is shown in Fig. 2: T_1 is the outlet pipeline temperature of primary circulation of refrigerant, and the difference between T_1 and target temperature is a constant value; T_2 is the temperature of the heat exchanger inlet; T_3 is the temperature of the heat exchanger outlet; T_4 is the inlet air temperature; T_5 is the outlet air temperature.

The secondary refrigerant circulation pipeline adopts the constant flow variable temperature control method. By controlling the opening of the return valve and bypass valve, the temperature of the heat exchanger inlet is adjusted, so as to realize the control of the air supply temperature T5 at the outlet of the heat exchanger.

3.2 The Analysis of Temperature Control Algorithm

For the climate laboratory shown in Fig. 1, if an ordinary single-loop PID controller is used for laboratory's temperature control, when the laboratory temperature deviates from

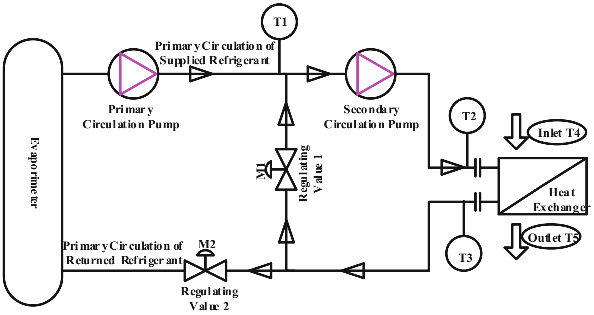

Fig.2. Refrigerant temperature control in the secondary refrigerant circulation system

the set value, the PID will adjust the temperature by changing the opening degree of the refrigerant regulating valve according to the magnitude and the positive and negative of the deviation value. However, this control accuracy of this control scheme is greatly low far from achieve the control of the climate laboratory. The reason is that the temperature control of the climate laboratory can be approximated as a first-order inertial system with a lag [12, 13]. If the temperature of the refrigerant fluctuates, the temperature of the supply air after the heat exchanger will change, and the circulating air will be recirculated. Enter the laboratory from the swirl tuyere of the air supply section. After a period of mixing, the temperature of the laboratory will deviate, and the control system will find the existence of interference, and then change the opening of the refrigerant regulating valve. Temperature is controlled. But this process has to go through the heat transfer of the heat exchanger, the process air entering the laboratory, and the air remixing, which is a link with a big lag. When the adjustment process takes effect, the temperature of the laboratory deviates far from the set value, resulting in large fluctuations in the laboratory temperature and reduced system stability [14].

Based on the above analysis, the feedforward-cascade PID control system as shown in Fig. 3 can be used, which has two closed loops. The closed loop of the inner loop selects the supply air temperature that is closer to the regulating valve and has a smaller lag time as the secondary controlled variable, and the main controlled variable is the laboratory temperature of the outer loop. In this way, the leading effect of the inner secondary loop can be used to timely reflect the temperature of the supply air before the temperature fluctuation of the refrigerant interferes with the laboratory temperature, and the secondary controller can timely overcome it. Due to the short loop, minor lag and timely control of the inner secondary loop, the control quality of the supply air temperature has been improved [15]. At the same time, for the thermal load interference caused by the test piece, test equipment, lighting, etc. in the laboratory, the feedforward control can be used to offset or reduce the effect of laboratory temperature through the control function of the feedforward controller [16].

As the feedforward-cascade PID control system shown in Fig. 3, the input of the outer loop PID is the expected temperature of laboratory, and the deviation between it and the laboratory temperature feedback value is calculated by the PID to calculate the supply air temperature, and used as the input of the inner loop PID, the inner loop PID calculates the opening of the refrigerant return valve and the bypass valve, and adjusts

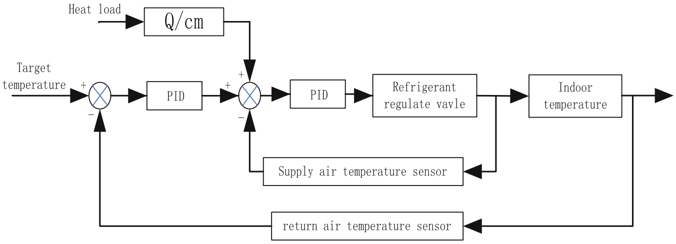

Fig. 3. Feedforward-cascade PID temperature controller

the temperature of the refrigerant at the inlet of the heat exchanger, thereby changing the supply air temperature and achieving the purpose of controlling the indoor temperature of laboratory.

A static feedforward controller [17] can be used in the feedforward link. The static feedforward controller calculates the temperature change value of the supply air caused by the heat load disturbance, and introduces it into the calculation of the supply air temperature deviation of the inner loop controller, so as to achieve the purpose of offsetting the heat load disturbance.

The supply air temperature change value is calculated by Eq. 10.

$$T_l = Q_l / c_a m_f \tag{10}$$

T_l is the change value of the supply air temperature. Q_l is the estimated heat brought by the indoor test piece and workin equipment. The c_a is the specific heat capacity at the current indoor temperature. The m_f is the air mass flowing through the circulating air heat exchanger per unit time.

In order to control the indoor temperature according to a certain heating and cooling rate, the laboratory temperature control belongs to the follow-up control system. The temperature target value (the input of the controller) is calculated by Eq. 11.

$$T_n = T_i + \frac{T_f - T_i}{t_c} \cdot t_k \tag{11}$$

T_n represents the current temperature target value. T_i represents the initial temperature. T_f represents the indoor final target temperature. The t_c represents the adjustment time from the initial temperature to the indoor final target temperature, and the t_k represents the adjusted time.

4 Application and Analysis

4.1 Parameters Tuning of PID Controller

The temperature control process of super large space climatic laboratory is a large time-delay object. As long as there is a temperature deviation, the function of the integral will continue. When the temperature deviation is large, integral saturation will exists and results overshoot of the temperature control curve. Therefore, integral separation PID is adopted for temperature control. When the deviation value is large, the integral effect is removed and PD control is adopted; when the deviation value is small, PID control is adopted [18]. The algorithm of incremental integral separation PID controller is

$$\Delta u(k) = K_p[e(k) - e(k-1)] + \beta(K_p/T_i)e(k)T + K_p * T_d[e(k) - 2e(k-1) + e(k-2)]/T \tag{12}$$

In formula (12), β is the integral separation coefficient, and ε is the integral separation threshold. If $e(k) > \varepsilon$, β is set to 0; If $e(k) < \varepsilon$, β is set to 1. In the temperature control of climatic laboratory, the integral separation threshold is set to 3.

According to the simulation method in reference [19], the MATLAB Simulink model is built, and the critical proportional method is used to turn the PID parameters of the system. The sampling period T must meet the Shannon sampling theorem. For the temperature control system with delay, the sampling period can be 1/10 of the pure delay time, so the sampling period is 9s. Set the integral coefficient and differential coefficient of PID controller to zero, so that the control system has only proportional component. Gradually increase the proportional coefficient $K_p^{'}$ until the system response appears equal amplitude oscillation. At this time, the s proportional coefficient $K_p^{'}$ is the critical scale δ_k, and the time taken for one oscillation is T_k.

According to the calculation method of critical proportional method, the empirical formula for the calculation of PID parameters is shown in Table 1.

Table 1. Empirical formula of critical proportion method

Parameters	*Kp*	*Ti*	*Td*
PID	$1.7\delta_k$	$0.5T_k$	$0.125T_k$

This method is used to turn the PID parameters of the sub controller and the main controller, and then a set of PID parameters are obtained (as shown in Table 2.) through fine-tuning trial based on the parameters.

Table 2. PID tuning parameters of main-loop and vice-loop

Parameters	*Kp*	*Ti*	*Td*
Sub controller	0.12	81	9.5
Main controller	0.35	410	110

4.2 Result Analysis

The feedforward cascade PID temperature controller is applied to the super large space climatic laboratory. The temperature process control includes cooling process

(+21°C→−20°C→-40°C→-45°C→−55°C) and heating process (−55°C→−40°C→-45°C→ + 21°C), and the temperature control curve is shown in Fig. 4. In each stage of heating and cooling process, the temperature regulation rate is consistent with the target rate, and the temperature fluctuation is less than ±2°C.

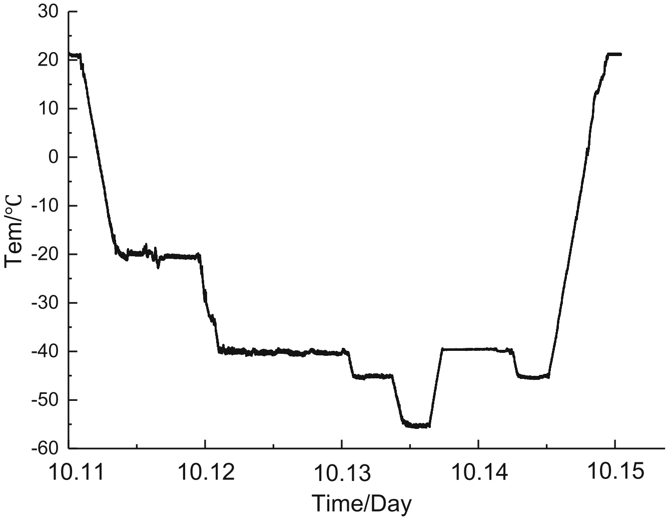

Fig.4. The temperature control curve

5 Conclusion

The large space climatic laboratory adopts feedforward-cascade PID for temperature control. The cascade PID controller overcomes the temperature fluctuation of refrigerant, and the feedforward controller overcomes the heat load interference caused by aircraft and working test equipment in the laboratory. The test results show that the established model can reflect the characteristics of the temperature control system of the climatic laboratory. The control method can effectively overcome the thermal disturbance, and it has fast dynamic response, high steady-state accuracy and no overshoot. The test results show that the temperature fluctuation is less than ±2°C.

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