IETI Transactions on Computers, 2016, Volume 2, Issue 2, 89-98.
http://www.ieti.net/tc
An International Open Access Journal

Two-Degree-of-Freedom Control to Low-Temperature Test

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Keywords: low-temperature test, temperature control, two-degree-of-freedom control, predictive control.

Abstract. Since environmental suitability is one of the vital properties of weaponry, environment test is the necessary measure to improve weaponry's environmental suitability, in which temperature control is a key part. It is necessary to investigate the temperature control methods which could enable the system to track setting smoothly, to reject disturbances effectively, and to response rapidly. In this paper, we design a 2DF controller firstly. Then, Smith predictive control is introduced to the 2DF control system, which is good at the ubiquitous time-lag in temperature control systems. The Smith-2DF control makes system to response faster with less overshoot, to track input and regulate disturbances synchronously and separately.

Introduction

Since environmental suitability is one of the vital properties of weaponry, environment test is the necessary measure to improve weaponry's environmental suitability [1]. The facility-aided artificial simulative environment experiment is good for controlling experiment conditions and test period accurately, good for reproducing and analyzing experiment results, and good for evaluating environmental suitability of the weapons [2]. In simulative environment test, temperature control is a key part which is linked to many tests (high and low temperature-humidity test, solar radiation test, thermal shock test etc.). In these tests, both security and availability of data are closely related with the control performance to temperature. On the other hand, there is ubiquitous time-lag in temperature control system. And the overshoot and oscillations which could be caused by start/stop to facility and abrupt changes of setting orders may lead the destruction to robustness. Therefore, it is necessary for improving the control performance of environment test to investigate the temperature control methods which could enables the system to track setting smoothly, to reject disturbances effectively, and to response rapidly.

Proportional-integral-derivative (PID) controllers have been used extensively in controlling temperatures at various temperature regimes such as very low temperatures [3] and high temperatures [4]. Pongam *et al*. proposed an opened-loop identification and thermal principles to estimate the mathematical model of the slab reheating furnace walking beam type and designed a suitable input (open/close burner) with the desire temperature response in heating up curve process [5]. O'Keefe *et al*. designed a time-varying PI temperature controller which affected the stack temperature by changing the flow rate of cooling water that passes across the stack, and employed it to a water-cooled 5kW hydrogen fuel cell stack [6]. Boldbaatar *et al*. designed a self-learning fuzzy sliding-mode controller and employed it to a water bath for temperature control [7]. Wu *et al*. designed a fuzzy controller for indoor environment temperature control [8]. Basak *et al*. designed a PID logic driven PWM controller for temperature control of Guarded Hot Box Test Facility [9]. These investigations are based on one-degree-of-freedom structure in which the regulations to system tracking performance and anti-disturbance performance are closely related to each other. The improvement to any of them would cause the degradation of the other one. Therefore, in this paper, we analyze the architecture of a kind of low-temperature test chamber firstly and then deduce the temperature system model. A 2DF controller is designed which includes a PID tracking controller and a D anti-disturbance controller. The designed 2DF controller keeps system to track reference input and to regulate disturbances synchronously and separately. Then, Smith predictive control is introduced to the 2DF control system, which is good at the ubiquitous time-lag in temperature control systems. The Smith-2DF control makes system to response faster with less overshoot.

System Modeling of Low-Temperature Test Chamber

During the heat circulation in low-temperature test chamber which is shown in Fig. 1 [10], the input heat (Q_{in}) is a function of air supplement (G_{in}), air-supplement temperature (T_{in}) and air specific heat capacity of the chamber (C_{in}).

$$Q_{in} = G_{in} T_{in} C_{in} \tag{1}$$

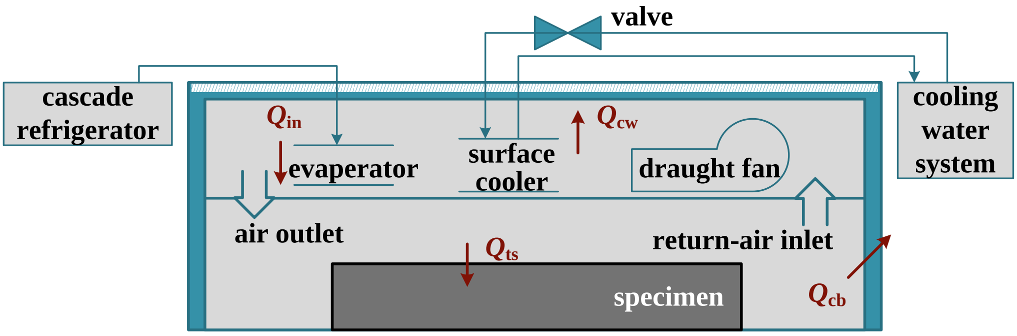

Fig. 1. Heat circulation in low-temperature test chamber

In the chamber, the heat consumption, Q_{out}, could be formulated as Eq. (2), which mainly includes heat consumption of cooling water (Q_{cw}), heat absorption of the specimen (Q_{ts}), and heat-transfer capacity of chamber inner wall (Q_{cb}).

$$Q_{out} = Q_{ts} + Q_{cw} + Q_{cb} \tag{2}$$

Each heat loss could be calculated as follow:

$$Q_{cw} = \rho_{cw} C_{cw} W_{cw} \cdot (T_{im} - T_{ex}) \tag{3}$$

$$Q_{ts} = C_{ts} M_{ts} \cdot \frac{dT}{dt} \tag{4}$$

$$Q_{cb} = \alpha_{cb} A_{cb} \cdot (T - T_{os}) \tag{5}$$

where ρ_{cw} denotes cool water density, C_{cw} cooling water specific heat capacity, W_{cw} cooling water flow, T_{im} initial temperature of cooling water, T_{ex} final temperature of cooling water, C_{ts} specimen specific heat capacity, M_{ts} specimen mass, T temperature at the return-air inlet, α_{cb} heat transfer coefficient of the chamber inner wall, A_{cb} heat-transfer area of the chamber inner wall, T_{os} temperature outside the chamber.

The heat in the chamber (Q) is the function which depends on return-air temperature (T), air specific heat at constant volume (C_V), air density (ρ_{cb}) and volume (V_{cb}) in the chamber.

$$Q = TC_V \rho_{cb} V_{cb} \tag{6}$$

According to the law of conservation of energy, the rate of change of Q is:

$$\frac{dQ}{dt} = Q_{in} - Q_{out} \tag{7}$$

Substitute Eqs. (1)-(6) into Eq. (7) to obtain:

$$C_V \rho_{cb} V_{cb} \cdot \frac{dT}{dt} = G_{in} T_{in} C_{in} - \rho_{cw} C_{cw} W_{cw} \cdot (T_{im} - T_{ex}) - C_{ts} M_{ts} \cdot \frac{dT}{dt} - \alpha_{cb} A_{cb} \cdot (T - T_{os}) \tag{8}$$

$$(C_V \rho_{cb} V_{cb} + C_{ts} M_{ts}) \cdot \frac{dT}{dt} = G_{in} T_{in} C_{in} - \alpha_{cb} A_{cb} \cdot (T - T_{os}) - \rho_{cw} C_{cw} W_{cw} \cdot (T_{im} - T_{ex}) \tag{9}$$

The cooling water is the heat-exchange medium by flowing through surface cooler. The heat-exchange process could be formulated as Eq. (10) in which A_c and β_c are respectively heat-exchange area and heat transfer coefficient of the surface, V_{cw} the cooling water volume.

$$C_{\mathrm{cw}}\rho_{\mathrm{cw}}V_{\mathrm{cw}}\cdot\frac{\mathrm{d}T_{\mathrm{ex}}}{\mathrm{d}t}=C_{\mathrm{cw}}\rho_{\mathrm{cw}}W_{\mathrm{cw}}\cdot(T_{\mathrm{ex}}-T_{\mathrm{im}})+\beta_{\mathrm{c}}A_{\mathrm{c}}(T-T_{\mathrm{ex}}) \tag{10}$$

The temperature inner chamber (i. e. the temperature at the return-air inlet T) is mainly determined by cooling water flow (W_{cw}) and air-supplement temperature. Therefore, for the system, the state variable, the output, and the controlled variable are respectively $x=\begin{bmatrix}T\\T_{\mathrm{ex}}\end{bmatrix}$, $y=T$ and $u=\begin{bmatrix}T_{\mathrm{in}}\\W_{\mathrm{cw}}\end{bmatrix}$. Then, the state equations and output equation could be described as:

$$\begin{cases}\dot{x}=Ax+Bu=\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}x+\begin{bmatrix}b_{11} & b_{12}\\ 0 & b_{22}\end{bmatrix}u\\ y=Cx=\begin{bmatrix}1 & 0\end{bmatrix}x\end{cases} \tag{11}$$

where $a_{11}=\frac{-\alpha_{\mathrm{cb}}A_{\mathrm{cb}}}{C_{\mathrm{V}}\rho_{\mathrm{cb}}V_{\mathrm{cb}}+C_{\mathrm{ts}}M_{\mathrm{ts}}}$, $a_{12}=\frac{\rho_{\mathrm{cw}}C_{\mathrm{cw}}W_{\mathrm{cw}}}{C_{\mathrm{V}}\rho_{\mathrm{cb}}V_{\mathrm{cb}}+C_{\mathrm{ts}}M_{\mathrm{ts}}}$, $a_{21}=\frac{\beta_{\mathrm{c}}A_{\mathrm{c}}}{C_{\mathrm{cw}}\rho_{\mathrm{cw}}V_{\mathrm{cw}}}$, $a_{22}=\frac{W_{\mathrm{cw}}}{V_{\mathrm{cw}}}-\frac{\beta_{\mathrm{c}}A_{\mathrm{c}}}{C_{\mathrm{cw}}\rho_{\mathrm{cw}}V_{\mathrm{cw}}}$, $b_{11}=\frac{G_{\mathrm{in}}C_{\mathrm{in}}}{C_{\mathrm{V}}\rho_{\mathrm{cb}}V_{\mathrm{cb}}+C_{\mathrm{ts}}M_{\mathrm{ts}}}$, $b_{12}=\frac{\rho_{\mathrm{cw}}C_{\mathrm{cw}}T_{\mathrm{im}}}{C_{\mathrm{V}}\rho_{\mathrm{cb}}V_{\mathrm{cb}}+C_{\mathrm{ts}}M_{\mathrm{ts}}}$ and $b_{22}=\frac{T_{\mathrm{im}}}{V_{\mathrm{cw}}}$.

Correspondingly, transfer function of Eq. (11) is:

$$T(s)=\frac{b_{11}(s-a_{22})T_{\mathrm{in}}(s)+(b_{12}s-b_{12}a_{22}+b_{22}a_{12})W_{\mathrm{cw}}(s)}{s^2-(a_{22}+a_{11})s+(a_{11}a_{22}-a_{12}a_{21})} \tag{12}$$

Two-Degree-of-Freedom Control for Temperature System of Low-Temperature Test

Two-degree-of-freedom control (2DF control) structure was proposed by Horowitz in his book, titled "Synthesis of Feedback System", in 1963 [11]. As a rudiment of active-disturbance-rejection control, the 2DF control structure could regulate and optimize the tracking performance and anti-disturbance of control capacity of system synchronously and separately. It has been widely used in industrial control system.

The main goals of temperature control for low-temperature test chamber are:

a. to track the setting temperature accurately.

b. to reject various disturbances so as to keep the robustness of system.

c. to eliminate the time-lag which is ubiquitous for temperature control system.

To aim at the control goals *a* and *b*, employ 2DF control structure in temperature system of low-temperature test chamber as shown in Fig. 2. $T(s)$ is the plant as Ep. (12). $N_1(s)$ and $N_2(s)$ denote disturbances. $R(s)$ is reference input. C_1 and C_2 are respectively tracking controller and disturbance-rejection controller.

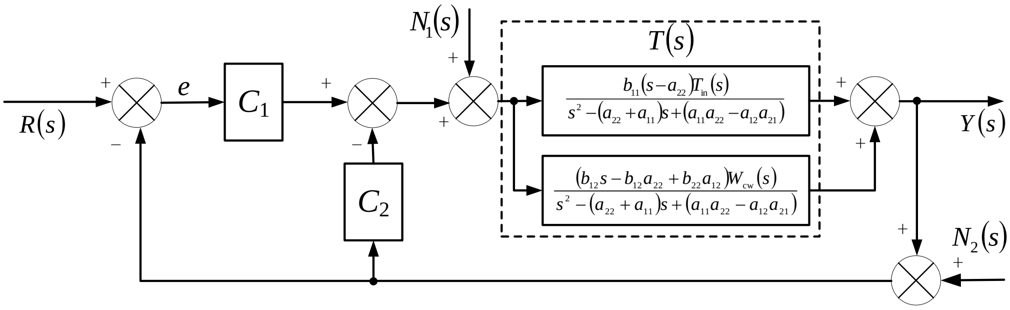

Fig. 2. 2DF control structure

The transfer functions are as Eq. (13) and (14). For a given G_{yn1}, G_{yn2} is always constant. But G_{yr} is various because it is independent of C_1 and G_{yn1}. For the three closed-loop transfer functions, G_{yr}, G_{yn1} and G_{yn2}, G_{yr} and G_{yn2} are independent of each other. Therefore, the system is a two-degree-of-freedom control system (2DF control system). To address the issue of improving system's response capacities, closed-loop characteristic and feedback characteristic could be regulated independently based on the 2DF control structure.

$$\begin{cases} G_{yr} = \dfrac{Y(s)}{R(s)} = \dfrac{C_1 T(s)}{1+(C_1+C_2)T(s)} \\ G_{yn1} = \dfrac{Y(s)}{N_1(s)} = \dfrac{T(s)}{1+(C_1+C_2)T(s)} \\ G_{yn2} = \dfrac{Y(s)}{N_2(s)} = \dfrac{(C_1+C_2)T(s)}{1+(C_1+C_2)T(s)} \end{cases} \tag{13}$$

$$\begin{cases} G_{yr} = C_1 G_{yn1} \\ G_{yn2} = \dfrac{T(s)-G_{yn1}}{T(s)} \end{cases} \tag{14}$$

The plant's parameters are chosen as Table 1.

Table 1 Parameters of temperature system in low-temperature test chamber

Parameter	Value	Unit	Caption
G_{in}	15000	kg/h	air supplement to the chamber
C_{in}	1	kJ/(kg ·℃)	air specific heat capacity of the chamber
ρ_{cw}	1030	kg/m^3	cooling water density
C_{cw}	3.92	kJ/(kg ·℃)	cooling water specific heat capacity
T_{im}	20	℃	initial temperature of cooling water
C_{ts}	0.21	kJ/(kg ·℃)	specimen specific heat capacity
M_{ts}	3.3	kg	specimen mass
α_{cb}	9.16e-5	kg/(m^2 ·℃)	heat transfer coefficient of the chamber inner wall

A_{cb}	54	m^2	heat-transfer area of the chamber inner wall
T_{os}	24	℃	temperature outside the chamber
C_V	0.72	kJ/(kg ·℃)	air specific heat at constant volume in the chamber
ρ_{cb}	1.2	kg/m^3	air density in the chamber
V_{cb}	27	m^3	air volume in the chamber
A_c	132	m^2	heat-exchange area of the surface cooler
β_c	57	$kg/(m^2$ ·℃)	heat transfer coefficient of the heat-exchange surface
V_{cw}	0.06	m^3	cooling water volume in the surface cooler

Let C_{total} denote C_1+C_2 which should be a PID controller as Eq. (15).

$$C_{total}=\frac{K(s+\alpha)(s+\beta)}{s} \tag{15}$$

Then, the closed-loop transfer function G_{ynl} could be:

$$\begin{aligned}G_{ynl}&=\frac{sT(s)}{s+T(s)K(s+\alpha)(s+\beta)}\\&=\frac{s[b_{11}(s-a_{22})T_{in}+b_{12}(s-a_{22})W_{cw}+b_{22}a_{12}W_{cw}]}{s(s-a_{22})(s-a_{11})-sa_{12}a_{21}+K(s+\alpha)(s+\beta)[b_{11}(s-a_{22})T_{in}+b_{12}(s-a_{22})W_{cw}+b_{22}a_{12}W_{cw}]}\end{aligned} \tag{16}$$

By the Zero-Placement, C_{total} could be determined as:

$$C_{total}=217.332+\frac{312.35}{s}+21.3s \tag{17}$$

The closed-loop transfer function G_{yr} could be transformed as:

$$\begin{aligned}G_{yr}&=\frac{C_1T(s)}{1+C_{total}T(s)}\\&=\frac{C_1[b_{11}(s-a_{22})T_{in}+b_{12}(s-a_{22})W_{cw}+b_{22}a_{12}W_{cw}]}{(s-a_{22})(s-a_{11})-a_{12}a_{21}+\left(21.332+\frac{38.35}{s}+2.13s\right)[b_{11}(s-a_{22})T_{in}+b_{12}(s-a_{22})W_{cw}+b_{22}a_{12}W_{cw}]}\end{aligned} \tag{18}$$

Controller C_1 is:

$$C_1=217.332+\frac{312.35}{s}+25.6s \tag{19}$$

Then controller C_2 could be determined as:

$$C_2=C_{total}-C_1=-4.3s \tag{20}$$

Simulate the temperature control system with Matlab/Simulink. Set the simulation time is 15s. The setting temperature is a step signal of which the initial value is 25℃ and final value -40℃ (i.e. simulate to regulate the temperature of chamber to cool from room temperature to low temperature).

Set the disturbances as the pulse signals in which $N_2(s)$ occurs at the 12th s with 6.5℃, $N_1(s)$ occurs twice: at the 4th s with 32.5℃ and at the 7th s with -6.5℃. Fig. 3 shows the system output with 2DF control. It demonstrates that 2DF control structure enables the system to keep good tracking performance with about 5℃ overshoot at the beginning of response, and to restrain the feedforward disturbances less than about 1/5 of themselves but for the feedback disturbance nearly half of itself.

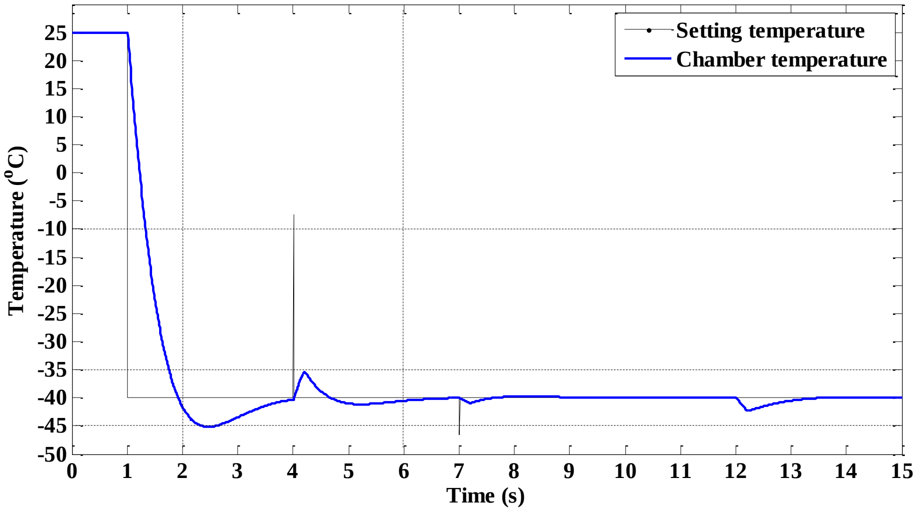

Fig. 3. Chamber temperature of the low-temperature test with 2DF control

Smith-2DF Control for Temperature System of Low-Temperature Test

Temperature control system is a typical time-lag system. It can be learned from Fig. 3 that the system output reaches the reference setting firstly at about the 2nd s, and reaches steady state after the 6th s. Of course, a disturbance signal occurs during the response process, which may lead the time-lag to reach steady state. At the steady state, after the feedforward disturbance occurs, it costs about 0.7s to return steady state. But it costs more than 1s to return steady state after the feedback disturbance occurs. To aim at the control goal *c* of temperature control for low-temperature test chamber and improve the response performance of the system, introduce Smith predictive control method in 2DF PID control structure as Fig. 4. Smith predictive control was proposed by Smith in 1957 to solve control delay [12], which predicts the possible response to uncertain disturbances and carries compensations to system through predictive model so as to eliminate the time delay.

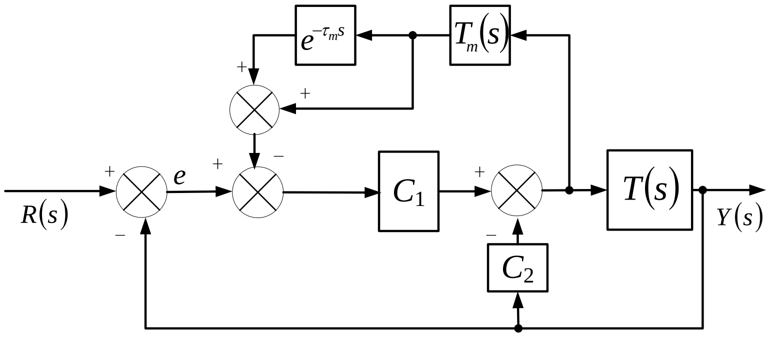

Fig. 4. Smith-2DF control structure

Smith predictive control is independent with control structure, and the predictive control parameters only relate to the dynamic characteristics of plant, the setting of control parameters is easy to implement. Let $\tau = 2$ and simulate. Fig. 5 shows the comparison for 2DF control and Smith-2DF control. In contrast with 2DF control, Smith-2DF control enables the system to response faster and with much less overshoot. It costs less time to reach steady state, nearly half of the 2DF-control. For the feedforward disturbances, Smith-2DF control performs stronger regulating capacity. Although the feedback disturbance could be regulated soon, its amplitude is not restrained very well. Fig. 6 shows the difference between two kinds of systems. It can be seen clearly that Smith-2DF control improves the response characteristics of temperature control system for low-temperature test.

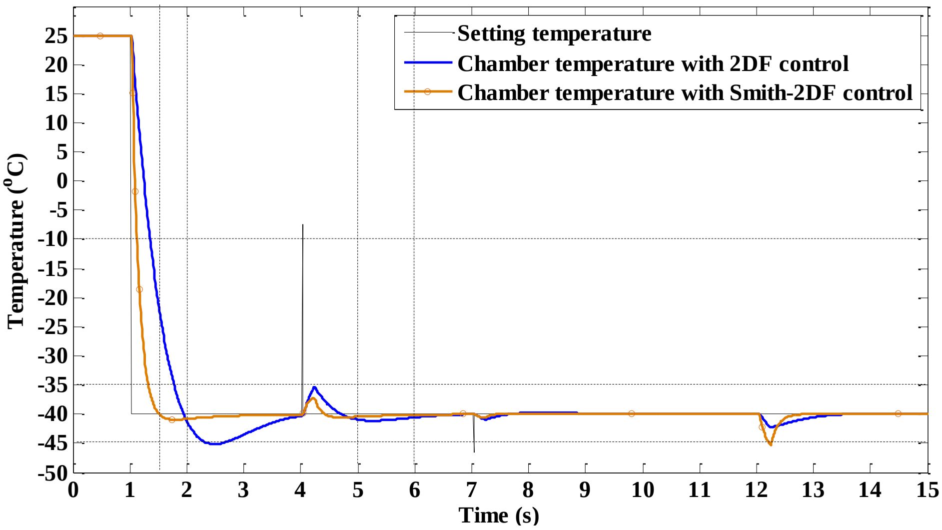

Fig. 5. Chamber temperature of the low-temperature test with Smith-2DF control

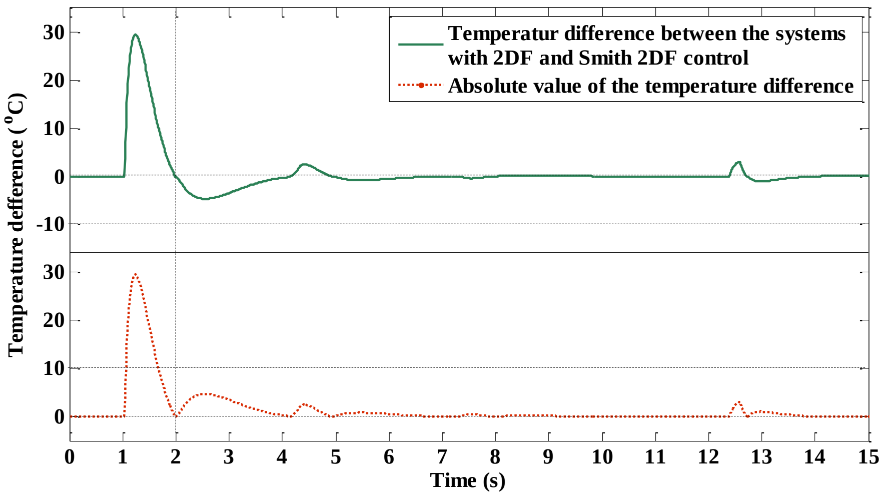

Fig. 6. Temperature difference between the systems with 2DF and Smith-2DF control

Conclusion

By analyzing the architecture of a kind of low-temperature test chamber, temperature system has been modeled. In order to make the temperature system to track setting value accurately and to reject various disturbances well synchronously and separately, 2DF controller has been designed with Zero-Placement and employed to the model. The simulation shows that there is still much time-lag during the response process. To address the time-lag which is ubiquitous for temperature control system, combine 2DF control structure and Smith predictive control for the system. The introducing of Smith predictive control enables the system to response and to regulate feedforward disturbances faster with less overshoot. But for feedback disturbance, its amplitude is not restrained significantly.

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