MODELING AND CONTROL OF TEMPERATURE OF HEAT-CALIBRATION WIND TUNNEL

by

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This paper investigates the temperature control of the heat air-flow wind tunnel for sensor temperature-calibration and heat strength experiment. Firstly, a mathematical model was established to describe the dynamic characteristics of the fuel supplying system based on a variable frequency driving pump. Then, based on the classical cascade control, an improved control law with the Smith predictive estimate and the fuzzy proportional-integral-derivative was proposed. The simulation result shows that the control effect of the proposed control strategy is better than the ordinary proportional-integral-derivative cascade control strategy.

Key words: *heat wind tunnel, temperature control, cascade control*

Introduction

The heat-calibration wind tunnel (HCWT) is a kind of the important experiment facilities to simulate the heat test environment with high temperature and high-speed airflow [1]. The temperature control of the heat-air-flow in HCWT is a challenge issue. Considering the airflow's speed of the wind tunnel is fixed within a certain experimental stage, so the temperature of combustor is mainly determined by regulating the flow rate of the fuel oil to be participated in burning. There are three kinds of method to realize the control the fuel flow rate: servo valve, variable pump, and variable-frequency-regulating-speed (VFRS) pump [2]. Petkovic *et al.* [3] researched the modeling of thermal system. Yu *et al.* [4] and Ren *et al.* [5] studied the fuzzy proportional-integral-derivative (PID) control in the temperature system. This paper mainly discusses the modeling and control of the temperature system of HCWT.

Model of HCWT

The studied HCWT and its control system block diagram are shown in figs. 1 and 2. HCWT consists of fuel supplying subsystem and temperature control subsystem. The establishment of HCWT model includes the model establishment for two subsystems.

Supposed that the variable frequency motor is operated as constant voltage-frequency ratio mode, its output rotational speed can be approximately expressed as:

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$$n_p = \frac{2\pi f(1-s_1)}{m_p} \tag{1}$$

where n_p [rs^{-1}] is the rotational speed of the motor, f [Hz] – the frequency of the motor, s_1 – the slip of the motor, and m_p – the pole-pairs of the motor.

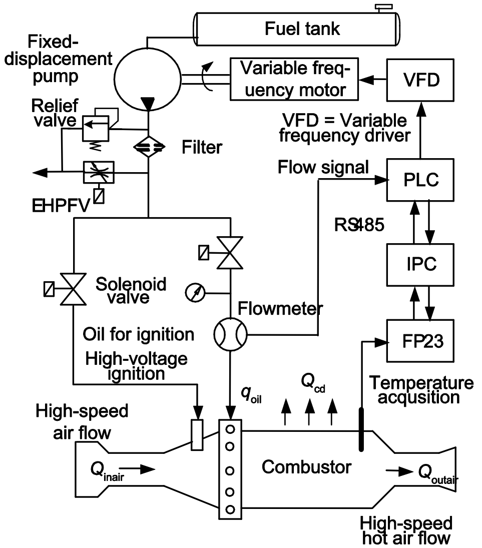

Figure 1. Fuel supply and control system

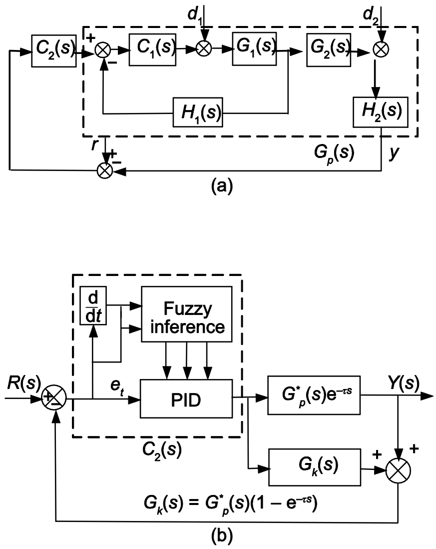

Figure 2. Block diagram of the control system

The flow continuity equation of the hydraulic supplying system is as:

$$q = n_p D - C_1 p - \frac{V_0}{\beta_e}\frac{\mathrm{d}p}{\mathrm{d}t} \tag{2}$$

where q [m^{3}s^{-1}] is the oil flow, D – the pump displacement, C_1 – the total leakage coefficient, p [Pa] – the oil pressure, V_0 – the total volume of pump and pipeline, and β_e – the elastic modulus of the fuel oil.

Assuming the fluid resistance R in supplying pipeline is linear, and substituting the flow rate formulas of thin-wall hole and the pipe line pressure loss into (2) yields:

$$q = \frac{2\pi f(1-s_1)}{m_p}D - C_1 R q - \frac{V_0 R}{\beta_e}\frac{\mathrm{d}q}{\mathrm{d}t} \tag{3}$$

where C_d is the flow coefficient, A_1 – the cross-sectional area of the hole, Δp – the pressure difference of the nozzle, ρ – the fuel oil density, $R = p/q = 2q_0[\rho(2C_d^2 A_1^2) + C_2]$, C_2 – the oil pressure loss coefficient, and q_0 – the flow at the fundamental frequency of 10 Hz.

Applying Laplace transform to eq. (3) yields the transfer function $G_1(s)$ as:

$$G_1(s) = \frac{q_{oil}(s)}{f(s)} = \frac{\left[\dfrac{2\pi(1-s_1)}{m_p}\right]D}{\dfrac{V_0 R}{\beta_e}s + C_1 R + 1} \tag{4}$$

By using the law of conservation of energy and mass conservation law yields the transfer function $G_2(s)$ of airflow's temperature system as:

$$G_2(s) = \frac{T(s)}{q_{oil}(s)} = \frac{K_p}{T_p s + 1} \mathrm{e}^{-\tau s} \tag{5}$$

where $K_p = (H\rho_{\text{oil}})/(\rho_{\text{inair}} q_{\text{inair}} c_p |_0^T + KA\alpha)$; $T_p = (V\rho_1 c_p |_0^T)/(\rho_{\text{inair}} q_{\text{inair}} c_p |_0^T + KA\alpha)$; H is the specific heat of the fuel, ρ_{oil} and ρ_{inair} are the densities of the fuel and the input airflow, ρ_{outair} – the density of the out-airflow, $c_p |_0^T$ – the specific heat capacity of the airflow of the combustor, K – the heat transfer coefficient of the combustor, A and V are the heat transfer area and the volume of the combustor, respectively, α is the scale factor, and ρ_1 – the density of the airflow in the combustor.

Control strategy and numerical simulation

Figure 2 is the block diagram of the cascade temperature control system. The proposed controller consists of three parts: inner PID, Smith predictive compensation, and out-loop fuzzy PID control. In fig. 2(a), $C_1(s)$ and $C_2(s)$ are the inner-loop controller and the out-loop controller, respectively, $H_1(s)$ and $H_2(s)$ are the transfer function of the flow sensor and of the temperature sensor, respectively. From fig. 2a, we can deduce the transfer function $G_p(s)$ as:

$$G_p(s) = \frac{C_1(s)G_1(s)G_2(s)H_2(s)}{1 + C_1(s)G_1(s)H_1(s)} = G_p^*(s)\mathrm{e}^{-\tau s} \tag{6}$$

In fig. 2(b), to design predictive compensator $G_k(s)$ and the fuzzy PID control law reject to the influences of the time lag and the time-varying parameters, respectively.

Parameters values in the numerical simulation model are shown in tab. 1.

Table 1. System model parameters

Symbol	Dimension	Value	Symbol	Dimension	Value
s_1		0.06	R	Pa/(m^3/s)	$1.67\cdot10^{10}$
m_p		3	H	J/kg	$4.29\cdot10^{7}$
D	m^3/r	$1\cdot10^{-5}$	ρ_{oil}	kg/m^3	790
V_0	m^3	$2.5\cdot10^{-3}$	ρ_{inair}	kg/m^3	1.293
β_e	Pa	$1.7\cdot10^{9}$	A	m^2	2.5
C_d		$5.07\cdot10^{-2}$	V	m^3	0.25
A_1	m^2	$1.885\cdot10^{-5}$	ρ_1	kg/m^3	1.4
C_1	(m^3/s)/Pa	$9.25\cdot10^{-11}$	$c_p \|_0^T$	J/(kg K)	1117
C_2	Pa/(m^3/s)	$6.88\cdot10^{13}$	K	W/(m^2 K)	25

Figures 3 and 4 are the simulation results the controlled temperature without disturbance and with disturbance, respectively. As shown in fig. 3, introducing Smith compensation and fuzzy PID in the cascade control system can significantly reduce the overshoot of the temperature control system, but also improved the steady-state performance of the system. As shown in fig. 4, while system exists disturbance (*e. g.* fuel oil flow rate impulse), Smith fuzzy PID cascade control has the better control effects than the conventional PID cascade control, especially, it has the better robustness.

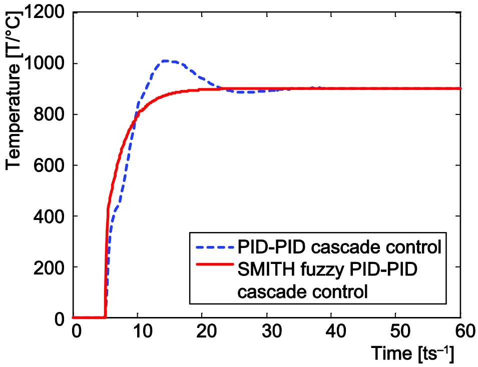

Figure 3. System simulation without disturbance

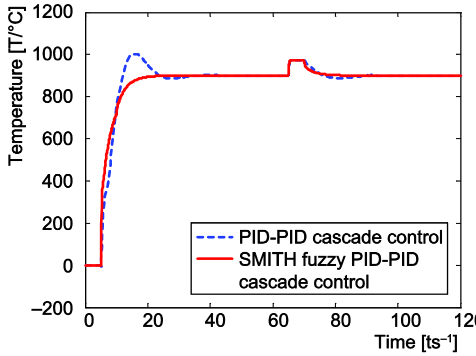

Figure 4. System simulation with disturbance

Conclusions

This paper mainly concerns with model and control for the fuel-oil flow rate and the output air-flow temperature of the combustor in HCWT. The theory analysis and simulation illustrates that the established mathematic model can approximately describe the dynamic characteristics of two subsystems of fuel-oil supplying and combustor in HCWT, and the proposed fuzzy PID control strategy with Smith predictor control can effectively solve the problems such as the large heat-inertia lag and the measuring lag existed in the cascade temperature control system. Moreover, the designed control law has also a certain restraining effect to the parameters time-varying and the disturbance existed in the plant.

References

[1] Zhao, S., Li, L., Chen, Y., 1700 °C Hot Wind Tunnel, *Aviation Metrology & Meas. Tech., 20* (2000), 4, pp. 3-6
[2] Peng, T. H., Xu, B., Yang, H. Y., Development and Research Overview on Variable Frequency Hydraulic Technology, *J. of Zhejiang Univ., 38* (2004), 2, pp. 215-221
[3] Petkovic, S., Pesic, R. B., Lukic, J. K., Experimental Verification of Mathematical Model of the Heat Transfer in Exhaust System, *Thermal Science, 15* (2011), 4, pp. 1035-1048
[4] Yu, H., Jia, J., Chen, G., Temperature Control of Electric Furnace Based on Fuzzy PID, *Proceedings, Int. Conf. on Electronics and Optoelectronics*, Shenyang, China (2011), Vol. 3, pp. 41-44
[5] Ren, D., Yao, J., Wang, Y., Dryer Surface Temperature Control System Based on Improved Self-Adaptive Fuzzy Smith Prediction Controller, *Proceedings, IEEE ICIT 2005*, Chengdu, China, 2005, pp. 1274-1279

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