Polymerizer Temperature Cascade Control System Based on Generalized Predictive Control

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Abstract

The polymerize process is the first stage in PAN-based carbon fiber production, and its temperature control affects directly the quality and yield of the last products. It has the serious time delay character if polymerizer temperature is controlled by the mixture of the hot water and the cold one, and the polymerization process will release a lot of heat. All these make it very complex to control the polymerizer temperature. The paper analyzes polymerizing technology firstly, then provides design and realization methods of polymerizer temperature cascade control based on generalized predictive control (GPC), and the system is realized through the control layer and the monitoring layer. The former realizes the model identification and the recursive computation in the generalized predictive control, and sends the results to the latter, and the latter realizes PID with dead-zone control of the mixed water temperature control using the results of the main regulator. The practice shows that the polymerize temperature cascade system runs well and has evident effect with effective control.

Keywords: polymerizing technology; generalized predictive control; cascade control

1. Introduction

PAN-based carbon fiber with the features of high strength, high modulus, high temperature resistance, fatigue resistance, creep resistance, electrical conductivity, thermal insulation and low thermal expansion coefficient etc., is a comprehensive new high-performance carbon material, being widely used in aviation, aerospace, chemicals and construction industries. At present, the domestic production of high-performance PAN-based carbon fiber is only tentative and the whole related technology level is very low.

As the first stage of the production of PAN-based carbon fiber, polymerizing process is that acrylonitrile (AN) and itaconic acid (IA) radical solutions react to synthesize the polyacrylonitrile spinning solution in the dimethyl sulfoxide (DMSO) solution initiated by azobisisobutyronitrile (AIBN) [1,2].
Polymerizing process system consists of public works, distillation purification, batching systems, polymerizing, monomer removal, defoaming and storage components. Specific process is shown in Figure 1, the public works provide non-ionized hot water and cold water for purification and polymerization; AN monomer and DMSO solution, through distillation and purification respectively, meet the required purity (more than 99.8 percent), and the monomers such as AN, IA etc., DMSO and initiator AIBN are configured in the batching system, then they are mixed and heated to polymerize in the polymerizer. At last, through monomer removal and defoaming in the reaction solution, the polyacrylonitrile spinning solution meeting the requirements was kept in storage kettle. Polymerizing is the basis of carbon fiber production and directly related to the quality and yield of the final products.

Polymerizer temperature control as a direct cause of impact on the reaction rate and product quality is the most important; furthermore, it is also the most complex because polymerizer temperature has serious time delay character caused by the mixture of the hot water and the cold one, and at the same time the polymerization reaction will release a lot of heat.

The paper designs an accurate, efficient and reliable polymerizer temperature cascade control based on generalized predictive control (GPC).

![Figure 1. Flow chart of polymerizing process](image)

2. **Polymerizer Temperature Control**

2.1 **Technology Requirement to Temperature**

Polymerizer temperature control is divided into three phases [3]:

Warming phase controlled by program. The reactants poured into the polymerizer are mixed fully and heated from the room temperature. The temperature is controlled to increase to 65°C stably after 2 hours.

Constant-temperature reaction phase. With automatic adjustment of cold water valve and hot water valve, the temperature in the polymerizer is strictly controlled within 65 °C ± 0.1 °C. About 15 hours later from the beginning of the reacting, the viscosity measurement circuit is opened. The reaction finishes when the polymer viscosity reaches 30Pa.s, and the whole process takes about 22 hours.

The end phase of the reaction. The temperature in the polymerizer is controlled to decrease to 50°C rapidly, and the reaction finishes.
2.2 Polymerizer Temperature Control

Polymerizer temperature is changed through regulating the opening of the cold and hot water valve. Polymerizer temperature control can use a cascade structure, and the frame is shown in Figure 2.

Figure 2. Frame of polymerizer temperature cascade control

The program calculates the set polymerizer temperature values, the main regulator outputs the set mixed water temperature based on GPC algorithm, the vice-loop adapts PID with dead-zone algorithm to control the opening of the cold and hot water valve to make the mix water temperature follow set values rapidly.

2.3 Characteristics of Polymerizer Temperature Control

The frequency in the main-loop is much higher than in the vice-loop, which makes temperature and pressure disturbance in the cold or hot water pipes is rapidly restrained, and the system disturbance rejection capability becomes stronger. At the same time, the rapidly restrained disturbance in the vice-loop can be regarded as a little model mismatching of generalized object, which makes the GPC regulator in the main-loop has good dynamic and robust properties. Furthermore the controlled object characteristics is improved by the cascade structure, its time constant is reduced with the increasing rapidity and the transition process takes only one minute. At last, the cascade system has stronger self-adaptive capacity to the equipment parameters changes and some non-linear effects.

3. Design of regulators

3.1 Main Regulator based on GPC

1) Algorithm steps

GPC as a model predictive control, has the characters of model identification, model predictive, rolling optimization and on-line correction. The function of prediction model is to predict the future output of the object based on historical information and the future input [4].

The vice-loop can be regarded as a generalized CARIMA model

\[ A(z^{-1})y(k) = B(z^{-1})u(k-1) + C(z^{-1})\xi(k) / \Delta \]

(1)

Where \( A(z^{-1}) \), \( B(z^{-1}) \), \( C(z^{-1}) \) are defined as

\[ A(z^{-1}) = 1 + a_1 z^{-1} + \cdots + a_n z^{-n} \]
\[ B(z^{-1}) = b_0 + b_1 z^{-1} + \cdots + b_n z^{-n} \]
\[ C(z^{-1}) = c_0 + c_1 z^{-1} + \cdots + c_n z^{-n} \]
Difference operator $\Delta$ is defined as $\Delta = 1 - z^{-1}$; $\xi(k)$ is white noise with zero mean.

The parameter identification uses recursive least square algorithm with fading memory [5]
\[
\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)\Delta y(k) - \varphi^T(k)\hat{\theta}(k-1)
\]
\[
K(k) = \frac{P(k-1)\varphi(k)}{\varphi^T(k)P(k-1)\varphi(k) + \mu}
\]
\[
P(k) = \frac{1}{\mu}[I - K(k)\varphi^T(k)]P(k-1)
\]

Where
\[
\theta = [a_1 \ a_2 \ \ldots \ \ a_{n_b} \ \ b_1 \ \ b_2 \ \ldots \ \ b_{n_b}]^T
\]

The initial parameters are assigned as
\[
\varphi(k) = \begin{bmatrix} -\Delta y(k-1) & \ldots & -\Delta y(k-n_y) & \Delta u(k-1) & \ldots & \Delta u(k-n_u-1) \end{bmatrix}^T
\]
\[
\theta(0) = [-0.94 \ 0.43 \ 0.65 \ 0.85 \ 0 \ 0.23 \ 0.47]^T
\]
\[
P(0) = \alpha^2 I
\]
\[
\alpha = 100
\]
\[
\mu = 0.95
\]

Where $\mu$ is forgetting factor.

The objective function is the following finite horizon quadratic criterion
\[
\min J(k) = E \left\{ \sum_{j=N_1}^{N_2} [y(k+j) - y_j(k+j)]^2 + \sum_{j=1}^{N_2} [\Delta u(k+j-1)]^2 \right\}
\]

Where $y$ is output expectation; $N_1$ and $N_2$ is the start and stop points of the optimization time horizon; $\lambda(j)$ is control weighting coefficient.

Building Diophantine equation (4)
\[
1 = E_x(z^{-1})A(z^{-1})\Delta + z^{-j}F_j(z^{-1})
\]
\[
G_j(z^{-1}) = E_j(z^{-1})B(z^{-1}) = \hat{G}_j(z^{-1}) + z^{-(j-1)}H(z^{-1})
\]

Through the recursive calculation $E_j(z^{-1})$, $F_j(z^{-1})$ and $G_j(z^{-1})$ can be gotten.

The $j$th step output of the generalized object is expressed as
\[
y(k+j) = G_j(z^{-1})\Delta u(k+j-1) + F_j(z^{-1})y(k) + H_j(z^{-1})u(k-1) + E_j(z^{-1})\xi(k+j)
\]

So the optimum control law to make the object function minimize is (5)
\[
u(k) = u(k-1) + d^T \left[ Y_x(k) - F(z^{-1})y(k) - H(z^{-1})\Delta u(k-1) \right]
\]

Where $d^T$ is the first line of the matrix $(\lambda I + G^T G)^{-1}G^T$.

2) Parameters selection

The optimization time horizon $P$ ($P = N_2 - N_1$) is very important to the stability of the control system. When control time horizon $N_u$ is very small and the control increment is not suppressed, a stable control can be achieved through increasing $P$.

Increasing $P$ and decreasing $N_u$ has a similar effect. In the practice design, $P$ is often regulated with a fixed $P$ [6].

Control weighting factor $\lambda$ can limit control increment $\Delta u(k)$ dramatic changes and reduce too large impact to the controlled object.
A smaller $\lambda$ can be selected firstly. If the system is stable and the manipulated value changes acutely, $\lambda$ value can be increased properly until a satisfactory control results.

After comprehensive analysis and repeated testing, the parameters are selected: $N_a = 4$, $N_b = 3$, $N_c = 1$, $P = 8$, $M = 4$, $\lambda = 0.01$.

3) Set value caculation

The set value of the main-loop is calculated by the program, and the specific algorithm is as follows

$$
Ts = \begin{cases} 
T_0 + \frac{65 - T_0}{120} \times t & \text{if } t < 120 \\
65 \cdots 120 & \text{if } t_0 \leq t < t_0 \\
50 \cdots t_0 & \text{if } t \leq t_0
\end{cases}
$$

In the formula, $Ts$ is the set polymerizer temperature; $T_0$ is the room temperature; $t_0$ is ending time for the temperature increasing; $t$ is the time of the polymerizer temperature control.

3.2 Vice Regulator based on PID with Dead-zone

The role of vice-loop is to make the mixed water temperature follows the main circuit output rapidly. The vice regulator utilizes PID control optimized by the dead-zone algorithm to prevent the pneumatic valve moving frequently.

The algorithm is as follows:

$$
u_i = \begin{cases} 
u_{i-1} \cdots e_i \leq \varepsilon_2 & \\
K_p \left( e_i + \frac{T}{T_i} \sum_{j=0}^{i} e_j + \frac{T_d}{T} (e_i - e_{i-1}) \right) \cdots e_i > \varepsilon_2
\end{cases}
$$

Parameters tuning based on the classic Z-N method [7], Which uses the 8:1 attenuation ratio, to obtain the final PID parameters as follows: $T = 6s$, $K_p = 10$, $T_i = 30s$, $T_d = 15s$, $\varepsilon_2 = 0.05$.

4. System Realization and Debugging

The polymerizer temperature cascade control system is made up of the monitoring layer and the control layer, and the fieldbus connects the both layers together [8].

The monitoring layer is made up of two workstations developed based on the iFix configuration software. Firstly, because the GPC algorithm is recursive and involves complex matrix inversion, it is calculated in the monitoring layer and then the result is sent for control layer applications through communication. Certainly it also has the functions of process flow graphs monitoring, parameter adjustment, historical trends inquiry, report forms statistics, real-time alarms, system administration and user login etc. The two workstations back-up each other, monitoring the whole polymerizing process [9].

The control layer is made up of field devices, instrumentations, programmable logic controllers and fieldbus. It receives the result of GPC algorithm and measures the polymerizer parameters and device status, then controls the valves to regulate concretely polymerizer temperature. The designed project is based on the PLC to ensure a high stability of the system.

In the debugging of the polymerizer temperature cascade control, it is found that pneumatic valves and mixing water temperature intense oscillation.

Analysis indicates the cause is that integration time are too long, the system needs much time to eliminate static error and mixing water temperature cannot go into dead-zone in a long time. So the
integration time constant of the PID parameters is reduced to enhance the role of integration, the pneumatic valve moves smoothly, and the mixing water follows the given temperature rapidly.

5. Conclusion

The paper analyzes polymerizing technology firstly, then gives the structure, character and realization method of a polymerizer temperature cascade control based on GPC.

After the polymerizer temperature cascade control system in the carbon fiber production is put into operation, the temperature control is accurate, timely, effective and the system runs stably with low consumption of material and energy, but with high quality of polyacrylonitrile spinning solution.

The practice shows that system structure and control method used in the paper fully meet polymerizing technology requirement, and at the same time it has certain universal reference significance to complex industrial processes such as the time delay, nonlinear and so on.

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References


