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Acrylic Polymerization Process Control and MATLAB Simulation Based on Intelligent Adaptive Control

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The polymerization process of acrylic fiber belongs to multi-input and multi-output nonlinear system. The polymerization continuous stirred reaction kettle temperature and polymerization conversion efficiency are important technological indexes in the polymerization production of acrylic fiber. The control level of the complex nonlinear process directly affects the differentiation rate of products. This study uses an intelligent self-adaptive control method to construct a mathematical model of acrylic fiber polymerization process, and the control method is designed in MATLAB. The corresponding simulation rules are made and the simulation of acrylic fiber polymerization process is completed.

1. Introduction

Acrylic fiber, also known as polynitrile propionitrile fiber, is fiber generally composed of acrylonitrile copolymer (acrylonitrile accounts for most) or homopolymer from the initiation of polymerization. Polymerization reaction is the main process in the process of acrylic fiber production, and its mechanism is complex and has strict indexes for technological operation and product quality. From point of view of production, the system is expected to achieve higher conversion under the premise of safe production. In terms of product quality, it is necessary to control the temperature so that the degree of polymerization of the product and its distribution meet technological requirements (Ulbrich et al., 2016). It is very difficult to control the polymerization because of the nonlinearity, strong miscibility and time-varying parameters of the polymerization reaction kettle.
Intelligent self-adaptive control is the use of a controller to make certain physical quantity of a controlled object automatically change in accordance with a predetermined law under the condition that no one is directly involved (Cervantes et al., 2015). Along with the progress and development of science and technology, the controlled object is becoming more and more complicated and the control accuracy of the controlled object is getting higher and higher, which leads to the sharp contradiction between complexity and accuracy. Intelligent self-adaptive control is one of the effective methods to solve the above problem (Xu et al., 2014). As a self-adaptive search algorithm, genetic algorithm can be applied as a good method because of its advantages in parameter optimization (Burgstaller et al., 2006).

2. Establishment of Mathematical Model for Polymerization Process of Acrylic Fiber

The polymerization of acrylic fiber belongs to free radical chain polymerization matrix. The reaction of acrylonitrile monomer to form high polymer includes chain initiation, growth, termination and transfer. The reaction is carried out in a continuous stirred reaction kettle with a cooled interlayer. In the reaction process, the mixture materials include monomer, initiator and solvent into the reaction kettle in a certain proportion. It is assumed that the reaction kettle is a full-mixed kettle, that is, materials can reach the molecular-level diffusion reaction process in a very short time in the full-mixed kettle where chain radical has equal activity. The reaction speed has no correlation with the length of active radical chain. The material ratio and the change in concentration in the reaction process have little effect on the reaction rate. At high conversion rate, the polymerization takes place in the polymer phase, and the reaction of the solution phase can ignore the transfer process and the disproportionation reaction (Altinten et al., 2010). The material energy balance in the polymerization kinetics process is as follows:

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$$\frac{dW_m}{dt} = -\frac{Q_{mf}}{\rho v}(W_{mf} - W_m) - k_p W_m C_r - 2fk_d W_i \frac{M_m}{M_i}$$
$$\frac{dW_i}{dt} = -\frac{Q_{mf}}{\rho v}(W_{if} - W_i) - k_d W_i \tag{1}$$
$$\frac{dT}{dt} = -\frac{Q_{mf}}{\rho v}(\frac{C_{pf}}{C_p}T_f - T) + \frac{UA}{\rho V c_p}(T_j - T) - \frac{k_p C_r W_m \Delta H}{M_m c_p}$$

Where,

$$C_r = \sqrt{\frac{fk_d C_1}{k_{ic}}}, C_i = \frac{W_1 \rho}{M_t}, C_m = \frac{W_m \rho}{M_m}, C_s = \frac{W_s \rho}{M_s}$$
$$\frac{1}{\rho} = \frac{W_m}{\rho_m} + \frac{W_s}{\rho_s} + \frac{W_p}{\rho_p}, W_p = 1 - W_m - W_s \tag{2}$$

Where, Q_{mf} is the mass flow rate of the reaction kettle, V is the capacity of the reaction kettle; W_m, W_s, W_i, W_p are the mass fraction of monomer, solvent, initiator and active chain in the reaction kettle respectively; T, T_f, T_j are the reaction kettle temperature, feedstock temperature, and interlayer temperature; C_m, Cs and C_r the molar concentration of monomer, solvent and initiator respectively in the polymeric kettle; M_m, M_s and M_t are the amount of molecules of monomer, solvent, and initiator; $x=[W_m, W_i, T]\in R^3$ is set as a system state vector; $u=[W_{if},T_j]^T\in R^2$ is the amount of operation. Considering the polymerization efficiency and process safety, T and W_m are the controlled output for the system (Su et al., 2010), namely $y_1=W_m$, $y_2=T$, and the system equation is simplified as:

$$\dot{x} = f(x) + \sum_{i=1}^{2} g_i(x)u_i, y_j = h_j(x), j = 1,2 \tag{3}$$

3. Intelligent Self-adaptive Control

Intelligent control is an advanced stage of the development of control theory, which is mainly used to solve the control problems of complex systems that are difficult to be solved by traditional methods. In particular, the research object of intelligent control has the following characteristics: uncertain model, high linearity; and complex task requirement.

3.1 PID control

The traditional PID controller is composed of a proportional unit (P), an integral unit (I), and a differential unit (D). The performance of the PID controller depends on the three coefficients, namely Kp, Ki and Kd. How to select these three coefficients is the core of PID control. A schematic block diagram of a traditional PID control system is shown in Figure 1,

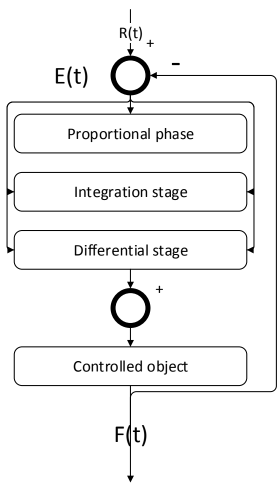

Figure 1: Schematic diagram of the PID control system

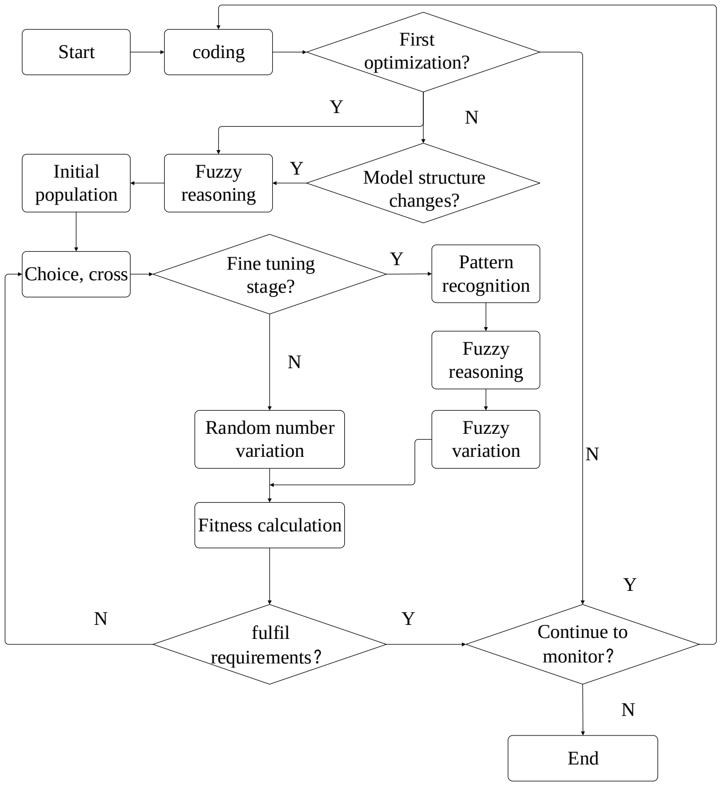

Figure 2: Algorithm flow

The control law is:

$$e(t) = r(t) - c(t) \tag{4}$$

Continuous form of PID controller

$$u(t) = K_p[(e(t)) + T_d \frac{de(t)}{dt} + \frac{1}{T_i}\int e(t)dt] \tag{5}$$

Discrete form of PID controller

$$u(k) = K_p * e(k) + K_i * \sum_{k,j\neq 0} e(j) + K_d * [e(k) - e(k-1)] \tag{6}$$

According to the characteristics of different objects and different control requirements, PID can be divided into PI, PD, PID, incremental PID, PID with separate integration, PID controllers with various filters. In the field of automatic control, many researchers combine the conventional PID control technology and the intelligent control technology organically to form many forms of intelligent PID controllers, such as, fuzzy PID control, neural network PID control, and intelligent self-correcting predictive PID control. The method of intelligent PID controller is to combine control fuzzy control, neural network, self-adaptive control and learning control with PID control method on the basis of PID controller to form a complex intelligent on-line variable mode PID controller (Monteiro et al. 2017). Table 1 gives a brief comparison of several intelligent PID control methods.

3.2 Algorithm design of intelligent self-adaptive control

For the parameter optimization problem of the above PID controller, it is transformed into the constrained optimization problem according to the ITAE standard. During the parameter optimization process, the search direction of the algorithm is always guided by the ITAE standard so that a set of PDI control parameters is obtained to minimize the fitness value J. Therefore, when the difference between the average value of the optimal individual fitness value and the contemporary optimal individual fitness value for several successive generations is within the required range, we can judge that the algorithm no longer has the ability to continue optimization, and then we can terminate the optimization of the algorithm. The detailed flow is shown in Figure 2.

Table 1: Comparison of several intelligent control methods

Methods	Information	Reference	Adjustment technique
Expert system control	$\sigma, \xi, e, \Delta e$	Thinking activities when manually determining PID parameters, theoretical analysis and experimental experience of system response summed up the rules of PID parameter adjustment	Automatically adjusted according to system response characteristics and control requirements
Fuzzy PID control	$e, \Delta e, \Delta y, e(k-1)$	Control law derived from control experience and PID control theory	Calculate the output based on the category of the input information
Network-based adaptive PID control	$e, \Delta e, \sum e$	No need	Online correction of control parameters by BP network
Adaptive PID Control Based on Dynamic Recursive Network	$y(k), e(k), e(k-1), \mu(k)$	Offline trained neural network object model	The BP algorithm is used to adjust the network online to obtain the parameters of the controller.

4. Simulation Analysis of Intelligent Self-adaptive Control

4.1 Establishment of simulation rules for fuzzy logic PID control

In MATLAB, the error e and the error change rate ec are the most input of fuzzy PID controller, which can meet the requirements of self-correcting PID parameters of e and ec at different time. Fuzzy control rules are used to modify PID control parameters on line and a self-adaptive fuzzy PID controller is constructed. Based on PID algorithm, fuzzy self-correcting PID carries out fuzzy reasoning by using fuzzy rules through calculating current system error e and error change rate ec. And parameter adjustment is carried out by querying fuzzy matrix table. The core of fuzzy control design is to summarize the technical knowledge and practical operation experience of engineering designers so as to establish a suitable fuzzy rule table. Table 2, Table 3 and Table 4 are fuzzy control rule tables respectively set for Kp, Ki and Kd.

Table 2: Kp's fuzzy rule map

E fuzzy state	EC fuzzy state			
	B	M	S	Z
B	B	VB	VB	VB
M	M	B	M	B
S	B	VB	VB	B
Z	VB	M	VB	B

Table 3: Ki's fuzzy rule map

E fuzzy state	EC fuzzy state			
	B	M	S	Z
B	S	S	S	S
M	M	M	B	VB
S	B	VB	VB	VB
Z	VB	B	VB	VB

Table 4: Kd's fuzzy rule map

E fuzzy state	EC fuzzy state			
	B	M	S	Z
B	S	M	M	VB
M	S	M	M	VB
S	S	VB	M	M
Z	S	M	M	VB

After the fuzzy rule tables of Kp, Ki, and Kd are established, self-adaptive correction of Kp, Ki, and Kd can be conducted according to the following methods. The system error e and the error coefficient ec are defined as the field e, ec = {0, 1, 2, 3} on the fuzzy set. The fuzzy set is e, ec = {B, M, S, Z}, and the elements in the subsets represent large, medium, small and zero respectively. The values of Kp, Ki and Kd are VB, B, M and S, which respectively represent large, large, medium and small. In the interface of fuzzy control, the membership of fuzzy subsets can be obtained. According to the membership evaluation table of each fuzzy subset and the fuzzy control model of each parameter, the fuzzy matrix table of PID parameters is designed by fuzzy synthesis reasoning. The on-line self-correction of PID parameters is accomplished by checking tables and operations through dealing with the results of fuzzy logic rules.

4.2 Simulation of polymerization process of acrylic fiber

The simulation parameters of the polymerization system are shown in Table 5.

Table 5: Polymerization simulation parameters

Parameter	Standard value	Parameter	Standard value
Q_{mf}	0.05kg/s	Cp	2500Jkg/K
V	1m3	C_{pF}	2638 Jkg/K
pm	850kg/ m3	Mm	0.193kg/mol
ps	1100 kg/ m3	Ms	0.023 kg/mol
pp	1224 kg/ m3	Mi	0.172 kg/mol
W_{mf}	0.8	R	8.145
W_{sf}	0.09	H	74390J/mol
Tf	287.33K	ua	1320Wm2/K

The initial value of the system state in the simulation process is [W_m, W_i, T]=[0.9,2e^{-4}, 300]. If the temperature in the polymerization kettle is required to reach 333 K, the monomer mass fraction is 0.3. The system temperature in the first stage of the simulation process is set to 330 k and the system temperature in the second stage of the simulation is set to 350 k. The conversion rate in the two stages is required to be 70%. The simulation curve is shown in Figure 3.

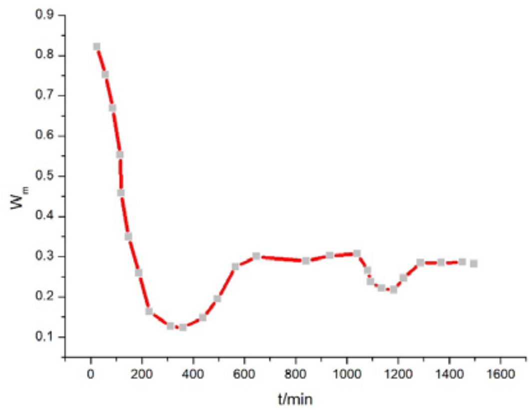

Figure 3: Monomer mass fraction

Figure 3 is a state variable of the reaction kettle system and Figure 4 is a monomer conversion rate. The reaction kettle temperature of the system is 300 k at the start-up stage. The monomer concentration in the reaction kettle is high and the conversion rate of the polymerization reaction is low. As the polymerization exothermic reaction proceeds, the temperature in the reaction kettle increases to 330 k and the conversion rate reaches 70%. The average molecular weight is an important index of the polymerization product, and the molecular weight is usually adjusted by adjusting the reaction kettle temperature. In the second stage of the simulation process, the system adjusts the reaction kettle temperature to 350 k according to the technological requirements, and the reaction conversion is still maintained at 70%. The simulation result shows that the control system realizes decoupling control of reaction temperature and conversion rate under the action of the controller. Under the premise of high polymerization conversion efficiency, the system can control the number average molecular weight and polymerization degree distribution of the polymerization reaction by adjusting the reaction kettle temperature, thus achieving the purpose of quality control of the polymerization reaction.

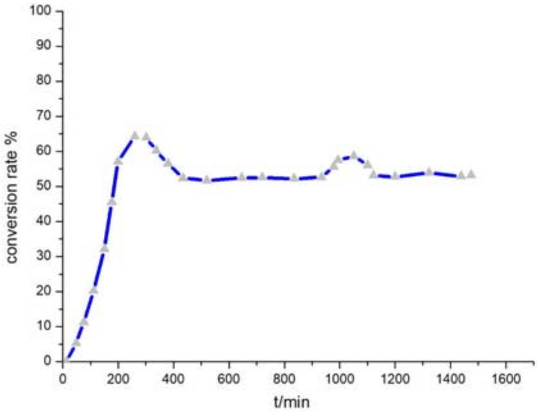

Figure 4: Conversion efficiency of the reactor

5. Conclusion

The control of polymerization is an important index of polymerization production. In this study, an intelligent self-adaptive control algorithm is designed, and the corresponding simulation flow is established by MATLAB. The decoupling control of conversion rate and temperature of the reaction kettle is completed. Under the premise of ensuring the conversion efficiency of polymerization, the temperature of polymerization kettle is adjusted to meet the technological requirements of different products. The method is of great significance to improve the properties and differentiation rate of acrylic polymer products.

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