Comparison of Three Adaptive Control Schemes

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ABSTRACT

A major characteristic of polymerization reactors is their complex nonlinear behaviour. Due to this nonlinear nature, control of polymerization reactors has always been a challenging task. In this article the performances of three adaptive control schemes, namely, self-tuning control(STC), adaptive internal model control (AIMC) and adaptive robust generic model control (ARGMC) are compared through simulation studies. The temperature control of polymerization of methyl methacrylate (MMA), which is highly exothermic, is chosen for simulation. Simulation results show that all three schemes can control the process but the best performance belongs to STC scheme.

Key Words: adaptive control, batch reactor, recursive identification, suspension polymerization

INTRODUCTION

Temperature control of a batch polymerization reactor, due to nonlinear behaviour of the process, is considered as an interesting area of research in chemical process control. In a batch reactor the reactants should be heated initially and after the start of reaction, heat has to be removed from the system for the case of exothermic reactions. After the decrease of the reaction and heat generation rate, it may become necessary to re-introduce heat to the system. Therefore, the control system should be capable of heating and cooling the reactor.

A major characteristic of a polymerization reaction is its nonlinear behaviour. The process gain and time constants vary with time usually within a wide range during a batch cycle. In the present work the performances of three adaptive control schemes are compared through computer simulations. The polymerization of methyl methacrylate (MMA) which is highy exothermic is chosen for simulation studies.

PROCESS MODEL

Polymethylmethacrylate (PMMA) is produced by suspension, emulsion, bulk and solution polymerization.

For simulation study the suspension polymerization is preferred to other methods because of the relative ease of polymerization control (heat removal and mixing). A schematic diagram of the process is shown in Figure 1.

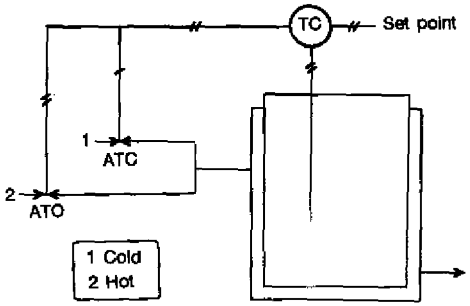

Figure 1. Schematic diagram of the reactor.

The temperature of the reactor is controlled by manipulating the flow rates of hot and cold streams that are mixed and enter the reactor jacket. Silicone oil is used as a heat transfer fluid. The temperatures of hot and cold streams are 150 °C and 25 °C, respectively. The volume of the simulated bench scale reactor is 5 L. The initial reactor temperature is 25 °C and it is desired to control the reaction at 90 °C.

The polymerization of MMA proceeds by a radical chain growth mechanism. In this work the kinetic model proposed by Ross and Laurence[1] is used for simulation. According to this model the monomer conversion is given by:

$$\frac{dx}{dt} = k_p \left[\frac{2fk_dI}{k_t}\right]^{1/2} (1-x) \tag{1}$$

Where:

$$f = 22.5I + 0.487 \tag{2}$$

and reaction heat generation rate, Q, is given by:

$$Q = -\Delta HM_oV_p \frac{dx}{dt} \tag{3}$$

The energy balance for the reactor gives:

$$\rho_r V_r C_{pr} \frac{dT}{dt} = h_i A(T_j - T) + Q \tag{4}$$

Taking Laplace transform from eqn (4) yields :

$$T(s) = \frac{1}{\tau_p s + 1} [T_j(s) + a\,Q(s)] \tag{5}$$

Where:

$$\tau_p = \frac{\rho_r V_r C_{pr}}{h_i A} \tag{6}$$

$$a = \frac{1}{h_i A} \tag{7}$$

As can be seen the transfer function between T_j and T is a first order model. To get a better estimate for the process transfer function an experiment was conducted on a 5 L bench scale reactor in the absence of polymerization reaction. A step change was applied to T_j and the reactor temperature was recorded. A first order model plus dead time was fitted to the recorded temperature, and the following transfer function was obtained:

$$G_p(s) = \frac{ke^{-\tau_d s}}{\tau_p s + 1} \tag{8}$$

Where k, τ_d and τ_p are 0.9, 60 and 915 s, respectively.

The heat generation rate, Q, is obtained from eqn (3). For controller design the process is modelled by an ARMA model and the heat generation term is considered as an unmeasured load.

If u(k), y(k) and ξ (k) denote input, output and load, respectively the ARMA model is given by :

$$A(q^{-1})\, y(k) = q^{-d} B(q^{-1})\, u(k) + \xi(k) \tag{9}$$

Where A and B are polynomials in backward shift operator :

$$A(q^{-1}) = 1 + \sum_{i=1}^{n} a_i q^{-i} \tag{10}$$

$$B(q^{-1}) = \sum_{i=1}^{n} b_i q^{-i} \tag{11}$$

Eqn (9) can be written in the following form :

$$y(k) = \phi^T(k)\, \theta_0 + \xi(k) \tag{12}$$

Where :

$$\phi^T(k) = [-y(k-1) \ldots, -y(k-n), u(k-d) \ldots u(k-d-m)] \tag{13}$$

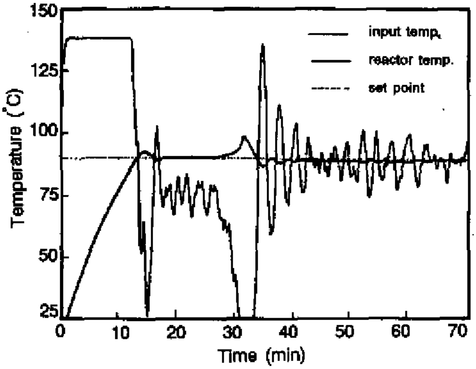

Figure 2. The system response using STC for nominal case.

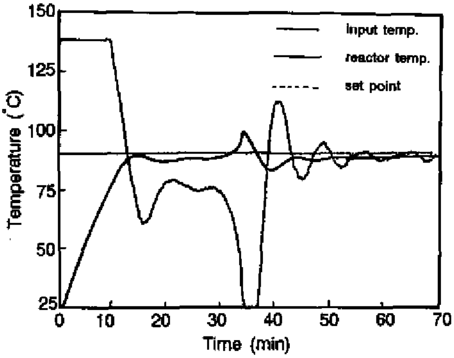

Figure 4. The system response using ARGMC for nominal case.

$$\theta_0^T = [a_1 ... a_n,\ b_1 ... b_m] \tag{14}$$

In all adaptive control schemes, which is to be considered later, the recursive least squares method with variable forgetting factor, λ, [2] is used. The corresponding equations are given below:

$$\theta(k) = \theta(k-1) + \frac{p(k-1)\,\phi(k)}{\lambda + \phi^T(k)\,p(k-1)\,\phi(k)}\,e(k) \tag{15}$$

$$p(k) = \frac{1}{\lambda}\,p(k) - \frac{p(k)\,\phi(k)\,\phi^T(k)\,p(k-1)}{\lambda + \phi^T(k)\,p(k-1)\,\phi(k)} \tag{16}$$

$$\lambda(k) = \max\begin{cases} 1 - \dfrac{e^2(k)}{1 + e^2(k)} \\ \lambda\text{min} = 0.98 \end{cases} \tag{17}$$

ADAPTIVE CONTROL SCHEMES

The performances of three adaptive control schemes are compared through simulation . These schemes are self-tuning control [3], adaptive internal model control [4] and adaptive robust generic model control [5]. The self-tuning controller (STC) based on the following cost function is used:

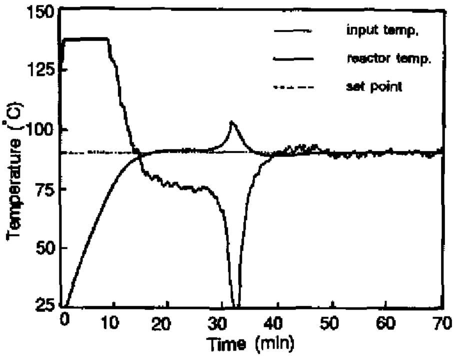

Figure 3. The system response using AIMC for nominal case.

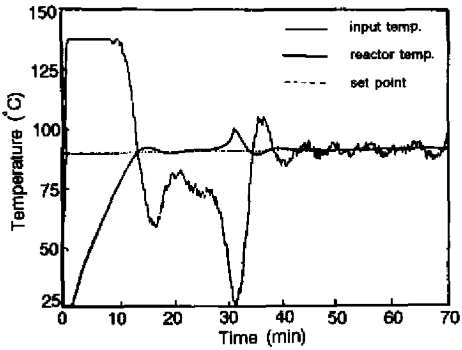

Figure 5. The system response using PID controller for nominal case.

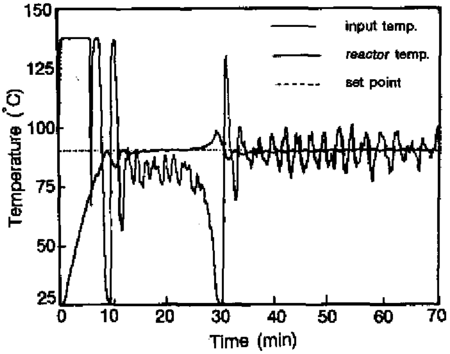

Figure 6. Effect of τ_p change on the STC performance.

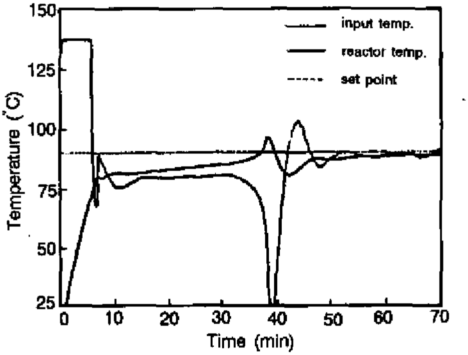

Figure 8. Effect of τ_p change on the ARGMC performance.

$$J = E\left[(y(k+d)-y_r(k))^2 + \mu\, \Delta u^2(k)\right] \quad (18)$$

where μ is a weighting factor for the control efforts and chosen to be 0.4.
The control law is given by:

$$u(k) = u(k-1) + y_r(k) - \phi^*(k+d) \quad (19)$$

where:

$$\phi^*(k+d) = Fy(k) + G\,u(k) \quad (20)$$

$$G = EB \quad (21)$$

and polynomials E and F are uniquely determined from the following Diophantin equation:

$$1 = AE + q^{-d} F \quad (22)$$

The second scheme used for comparison is the adaptive internal model control (AIMC). Internal model control was first proposed by Garcia and Morari [6]. In this design a filter is cascaded with the controller. In general an n'th order filter of the form $1/(\alpha s+1)^n$ is used. In this study a first order filter is used and the filter time constant α, is so selected to minimize the performance index J.

The third scheme considered for simulation

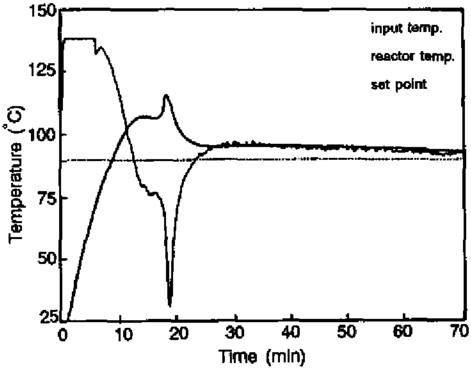

Figure 7. Effect of τ_p change on the AIMC performance.

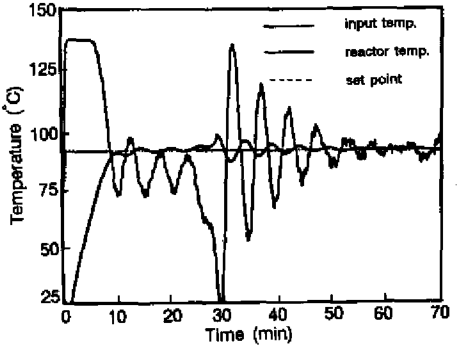

Figure 9. Effect of τ_p change on the PID controller performance.

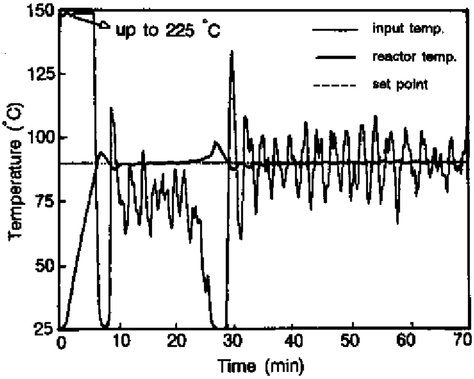

Figure 10. Effect of T_j change on the STC performance.

is the adaptive robust generic model control (ARGMC). Generic model control was proposed by Lee and Sullivan [7]. In the generic model control approach the process output rate is forced to match the reference rate. The reference rate is generated by the following equation :

$$r^* = k_1 (y_r - y) + k_2 \int (y_r - y)dt \qquad (23)$$

As can be seen the algorithm has two tuning parameters k_1, and k_2. Based on IMC structure, Lundberg and Bezanson [8] proposed the robust generic model control. Later on Rani and Gangiah [5] proposed the adaptive version of this scheme. This version is used for simulation and parameters

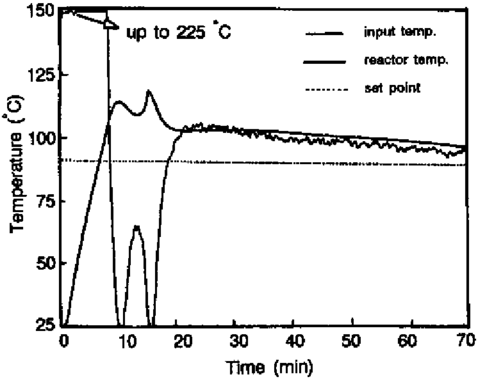

Figure 11. Effect of T_j change on the AIMC performance.

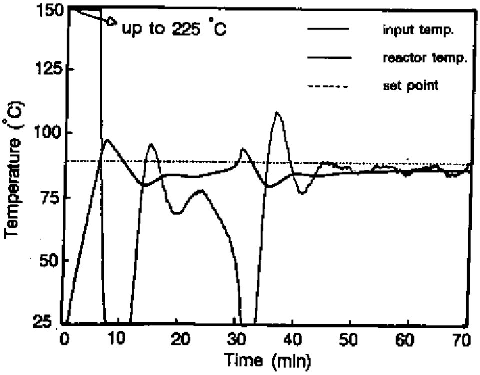

Figure 12. Effect of T_j change on the ARGMC performance.

k_1 and k_2 are so determined to minimize the cost function J.

COMPARISON OF CONTROLLERS PERFORMANCES IN THE NOMINAL CASE

To compare the performances of three aforementioned schemes, computer simulations are performed. The sampling period is chosen to be 0.2 τ_d, i.e. 12 s. A first order discrete model is used for all simulations. The initial temperature is 25 °C and the desired reactor temperature is 90 °C. The

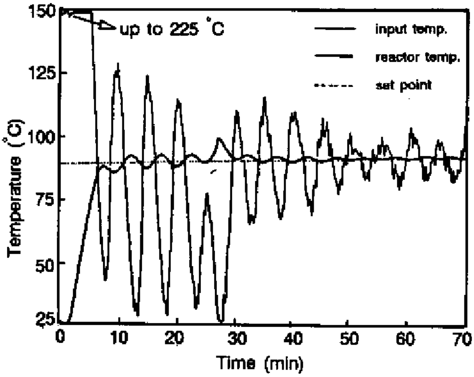

Figure 13. Effect of T_j change on the PID controller performance.

minimum and maximum temperatures of the fluid entering the jacket is 25 °C and 150 °C, respectively. In all runs the measurement noise with standard deviation of 0.2 is considered. The simulation results of the three schemes are shown in Figures 2–4.

As can be seen from the results, the performances of STC and AIMC are similar and slightly better than ARGMC's performance. A non-adaptive PID is also used for controlling the reactor temperature and the result is shown in Figure 5. As can be seen its performance is very similar to STC and AIMC, but when the operation conditions are changed or model mismatch is taken into account, its performance will deteriorate which will be shown in the next section .

ROBUSTNESS EVALUATION OF COMPARED ALGORITHMS

To compare the behaviours of the control schemes when there is model mismatch, simulations are performed. Two types of model mismatches are considered. In the first run the process time constant is reduced to about 30%. The results for PID and other three controllers are shown in Figures 6–9.

The best performance belongs to STC. Performances of AIMC and ARGMC are not satisfactory. The oscillations after gel effect are damped slowly for PID, but it still performs better than AIMC and ARGMC schemes.

In the second run the upper limit on T_j is changed from 150 °C to 225 °C.

The results are shown in Figures 10–13. As can be seen only STC's performance is acceptable.

CONCLUSION

In this study the performances of three adaptive control schemes are compared through simulations. The process considered for simulation is polymerization of MMA in a batch reactor.

The results indicate that in the nominal conditions, the performances of STC and AIMC are similar and slightly better than ARGMC's performance. When the process conditions are changed or model mismatches are taken into account, the best performance belongs to STC and performances of AIMC and ARGMC are not satisfactory.

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NOMENCLATURE

A,B,E,F,G: Polynomials in backward shift operator (q^{-1}).

a_i , b_i: Discrete model parameters.

A: Heat transfer area of the reactor's wall.

C_{P_r}: Heat capacity of suspension mixture in reactor.

d: Time delay expressed as an integer multiple of the sampling period.

e: Estimation error.

G_p: Process transfer function.

h_i: Inside reactor heat transfer coefficient.

I_o: Initial initiator concentration.

I: Initiator concentration.

k: Process gain.

k_1 , k_2: ARGMC tuning parameters.

k_d: Initiator decomposition rate constant.

k_c: PID controller gain.

k_p: Propagation rate constant.

k_t:	Termination rate constant.
n , m:	Known positive integer.
M_o:	Initiator monomer concentration in reactor.
q:	q operator.
Q:	Reaction heat generation rate.
r^*:	Reference rate (in ARGMC).
s:	Laplace operator.
T:	Temperature of suspension mixture in reactor.
T_j:	Reactor jacket temperature.
u:	Process input.
V_p:	Volume of monomer in reactor mixture.
V_r:	Volume of suspension mixture in reactor.
x:	Monomer conversion.
y:	Process output.
y_r:	Set point.

GREEK LETTERS

$-\Delta H$:	Heat of reaction.
α:	Time constant of filter in AIMC.
ϕ:	Regression vector and auxilliary output in eqn (18).
λ:	Forgetting factor.
θ:	Parameters vector.
ρ_r:	Suspension mixture density in reactor.
τ_d:	Process time delay.
τ_D:	PID derivative time constant.
τ_I:	PID integral time constant.
τ_p:	Process time constant.
ζ:	Noise disturbance sequences.