Temperature Control of Highly Exothermic Batch Polymerization Reactors

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ABSTRACT: In this article a highly exothermic batch polymerization reactor is considered. The reactor is simplified as a mixing tank with the internal heat generation treated as a disturbance. A fuzzy-hybrid–PID-feedback (FH-PID) control structure is developed in which the output of fuzzy hybrid portion is used to adjust the set point of a PID controller to compensate for the effect of the major disturbance, the heat of reaction. In this way, the hybrid portion of the controller does not influence the stability of the original PID control system. A fuzzy model was constructed to estimate the heat of reaction inside the fuzzy hybrid block. The fuzzy parameters of the hybrid portion do not depend on the process model and can be estimated from the transient response obtained with a conventional PID controller. This FH-PID control strategy has been applied to the temperature control of batch solution and batch inverse emulsion polymerizations of acrylamide in a 1 gallon pilot scale reactor. The results show that this fuzzy hybrid–PID-feedback control strategy improves the control performance of the batch polymerization reactor. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **63:** 761–772, 1997

Key words: acrylamide; batch polymerization; fuzzy hybrid; solution polymerization; inverse-emulsion polymerization; polymer reaction engineering

INTRODUCTION

The control of polymerization reactors is important due to the volume of products that are produced from a variety of monomers. Additionally, a range of polymeric properties, controlled largely by their molecular weight or composition, can be synthesized from any given monomer. These polymer properties are largely governed by the initial reagent concentrations, the temperature-conversion history, and reactor policies such as semibatch monomer feed strategies. For example, temperature has a reciprocal influence on the polymer molecular weight in free radical processes. These reactions are also typically exothermic; therefore, the temperature control of polymerizations has a significant influence on the quality of the product produced. This is true for a variety of commercial technologies, including emulsion, suspension, and solution polymerizations, as well as the aqueous based analogies such as inverse-emulsion.[1]

The temperature control of polymerizations has been investigated by several researchers. Garcia[2] applied quadratic dynamic matrix control to regulate the temperature of the polymerization of synthetic rubber in a semibatch reactor. This method used a linearization of a predetermined process model to predict the reactor temperature over a time horizon. Kiparissides and Shah[3] have evaluated two types of adaptive regulators applied to the batch suspension polymerizations of polyvinyl chloride. In their case, either the reactor temperature or the rate of reaction was controlled

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by varying the heat removal rate. Takamatu et al.[4] combined an internal model control and an adaptive parameter identification technique and applied it to a batch polymerization reactor. Farber and Ydstie[5] considered the implementation of an adaptive controller, which was based on a variable "forgetting factor" estimator, for the temperature control of a solution polymerization of styrene carried out in a continuous stirred tank reactor (CSTR). Whatley and Pott[6] considered the temperature control of an industrial polymerization unit and basically varied the controller gains according to the measured values of temperature to compensate for deviations from the linear conditions. Marini and Georgakis[7] theoretically studied the temperature control of a continuous low density polyethylene reactor. Daoutidis et al.[8] considered the feed forward/feedback control of a multivariable nonlinear process and applied this to a simulated polymerization reactor.

Although a significant amount of work has been carried out on the temperature control of polymerization reactors, this has most often focused on simulations. Furthermore, a mathematical model of the polymerization process is usually required, which presents additional demands. Batch polymerizations are very complex time-varying processes with virtually every engineering parameter changing as a function of conversion (e.g., viscosity, heat capacity of the polymer mixture, and heat transfer coefficient). It is also very difficult to measure the heat capacity and heat transfer coefficient precisely on-line. Therefore, the identification or adaptation of the process model on-line is problematic. In general, control strategies that are based on mathematical models of batch polymerizations are not applicable for industrial reactors, particularly for non-commodity polymers for which accurate models may not exist. It is for such processes for which kinetic and reactor models are either not available, or unreliable, that the approach developed in this article is primarily aimed.

Since Zadeh first developed fuzzy theory[9,10] as a base for determining operating conditions with nonprecise information, the technique of fuzzy control has been used successfully in processes with nonlinear, time-varying behavior. King and Mamdani[11] first applied a fuzzy logic controller to the temperature control of a stirred tank, which was a component of a batch reactor process. Later, Liu[12] designed a fuzzy temperature controller for a batch sulphonating reactor, and Ni et al.[13] designed a fuzzy controller for the purpose of avoiding overshoot. Rong and Wang[14] used a fuzzy control algorithm to control the temperature of a pilot scale propylene oxide polymerization process. Roffel and Chin[15] have applied fuzzy control principles to the control of a polymerization reactor and reduced the standard deviation of the target polymer property. Most of these investigations have used fuzzy algorithms to design fuzzy controllers, which replaced conventional PID controllers.

The conventional PID control method is inadequate for the temperature control of a batchwise polymerization with rapid heat generation from reaction[16] since the overshoot of reaction temperature can be more than two degrees even in a pilot scale reactor. For certain heterophase polymerizations, such an overshoot has the potential of causing gelation or latex instabilities and, consequently, a runaway reaction.[17]

In this paper, a highly exothermic batch polymerization reactor is considered. The heat generated by the polymerization reaction can be viewed as a disturbance; i.e., it is a cause of the deviation of the reaction temperature from the set point. The heat of reaction can be estimated from an energy balance on the reactor cooling water with the heat removed by the cooling water related to the reaction rate. If the heat of reaction can be viewed as a disturbance, and if we can estimate it by an energy balance, then the control structure developed herein is similar to measuring the disturbance in a flow reactor or CSTR and taking corrective action before the disturbance enters the process. One would normally designate this structure as a feed forward strategy. However, since we are measuring the disturbance as it occurs in the reactor, not before it enters, it is dissimilar to a conventional feed forward strategy. We might consider this a cascade controller. Normally, however, cascade policies are implemented to reject disturbances in the manipulated variable from entering the process. In our case, we manipulate a steam flow to maintain the cooling water inlet temperature at its set point. Since we estimate the heat of reaction from the energy balance and treat it as the major disturbance, we have another measured variable on which to initiate a control action. Therefore, the proposed controller has a feed forward/cascade hybrid structure.

A fuzzy-hybrid–PID-feedback control strategy has also been developed in which the set point of a PID controller is adjusted by the fuzzy hybrid (FH) block to compensate for the major disturbance, the reaction heat. The parameters of the

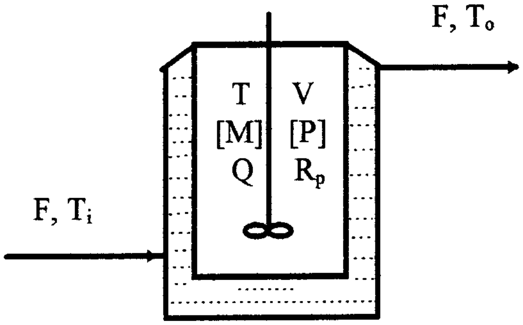

Figure 1 A schematic of a batch polymerization reactor. V is the reactor volume (L), T the internal reactor temperature (°C), $[M]$ the monomer concentration (mol/L), $[P]$ the polymer concentration, Q the heat generation (kJ/s), and R_p the rate of polymerization (mol/L s). F is the flowrate of the cooling water (L/s), and T_i and T_o are the respective inlet and outlet cooling water temperature (°C).

fuzzy hybrid portion of the controller are independent of any mathematical models for the polymerization. This strategy has been tested on the temperature control of batch inverse-emulsion and solution polymerizations of acrylamide.

System Analysis

Figure 1 shows a schematic of a batch polymerization reactor. If one assumes that the water in the jacket is mixed well, an energy balance on the reactor provides

$$C_v \rho V \frac{dT}{dt} = -UA(T - T_o) + Q \qquad (1)$$

where C_v is the heat capacity of polymer mixture inside the reactor (kJ/kg K), ρ is the density of polymer mixture (kg/L), and U is the overall heat transfer coefficient (kJ/m^2 K s). Since the propagation reaction dominates the polymerization mechanism for acrylamide, the long chain approximation is valid $\left(R_p \cong -\frac{\mathrm{d}[M]}{dt}\right)$ and the reaction heat (Q) is primarily generated from the reaction of monomer with growing macroradicals:

$$Q = VR_p q \qquad (2)$$

where q is the enthalpy of the polymerization.

An energy balance on the reactor and cooling system provides

$$Q = C_w F(T_o - T_i) + \rho V C_v \frac{dT}{dt} + Q_{loss} \qquad (3)$$

where Q_{loss} is the heat loss to the surroundings.

Equation (3) can be used to estimate the heat of reaction. Furthermore, if the temperature of the reactor is controlled well, and the temperature between jacket and the surrounding does not change significantly, Q_{loss} can be treated as a constant.

In this article, the heat generation Q is taken as a disturbance to the temperature control of the polymerization reactor. If the temperature of inlet cooling water is used to adjust the reaction temperature, the fluctuation of the cooling water flow rate F is a secondary disturbance. However, this flow rate can be controlled easily with a PID controller and, therefore, has a negligible effect on temperature compared with that of reaction heat and can be neglected. Thus, we propose to treat the heat generation Q as the major disturbance for the temperature control system. The reactor is then be simplified to be a mixing tank with a heat disturbance Q. Although heat generation is an implicit part of the reaction mechanisms, we have decoupled the reaction from the fluid agitation for the purpose of obtaining improved control. This simplifies the problem of the control system design for the reactor. Indeed, the control system design reduces to a mixing tank. It also provides very good temperature control, as will be discussed in the next section of this article.

For a process with only a single major disturbance, the most simple and efficient means to overcome the effect caused by the disturbance is via a feed forward control strategy with the major disturbance as the input of the feed forward block. This functions well, provided the disturbance can be measured and a process model identified. However, throughout a solution polymerization the concentration of polymer increases causing the viscosity of the polymer mixture to rise. The heat transfer coefficient U decreases with the conversion, while the heat capacity changes to a lesser extent. For example, in the inverse emulsion process, employed later in this article, the heat capacity of the initial reaction mixture (0.62 kcal/mol) decreases to 0.59 kcal/mol for the fully polymerized product. These changes render a batch polymerization a time-varying process, whose parameters cannot be measured precisely in an on-line manner. Since we cannot adapt the process model for our control purpose, the conventional adaptive control strategy, or any other model based systems, are not applicable for the control of acrylamide polymerizations.

Fuzzy Hybrid–PID Feedback (FH-PID) Control Strategy

Fuzzy theory describes logical knowledge by if–then production rules and represents subjects and ambiguities using membership functions. Fuzzy theories handle both objective logic and subjective intuition. Knowledge based models utilizing subjective thinking and judgment can also be constructed. In this work, a fuzzy model is generated for the estimation of the major disturbance, the heat of reaction, and fuzzy control rules of the FH portion are generated from the combination of feed forward control principles and the understanding of the batch polymerization of acrylamide.

Fuzzy Model for the Heat of Reaction

For a polymerization process, if the reaction temperature is not significantly higher than ambient, the third term on the right side of eq. (3) is small compared to the first two terms and can be treated as a constant throughout the polymerization. Equation (3) can then be normalized for fuzzification purposes, as follows:

$$Q_1 = C_w F(T_o - T_i) + \rho V C_v \frac{dT}{dt} \qquad (4)$$

The heat of reaction is divided into four fuzzy subsets: $\tilde{Q}\_0$ (zero), $\tilde{Q}\_1$ (small), $\tilde{Q}\_2$ (middle), and $\tilde{Q}\_3$ (big). Usually, the reaction rate reaches its maximum at approximately 10% conversion. Therefore, the major disturbance Q is greatest at the outset of the reaction, and this initial period of the polymerization is the most important in terms of the temperature control. A weighted heat capacity of the reactant mixture, $C_v = (3C_{v0} + C_{vf})/4$ has been chosen to represent the importance of this initial period and to determine in the fuzzy subset to which Q belongs (C_{v0} is the heat capacity of the monomeric mixture, while C_{vf} is the heat capacity of the fully polymerized sample). The fuzzification of the heat of reaction Q can be computed using eq. (4) and the membership functions shown in Figure 2. A membership function is a fuzzy logic term used to describe the extent to which an element belongs to a fuzzy subset.

Fuzzy Hybrid–PID Feedback Control Strategy

For the temperature control of highly exothermic polymerization reactors, in addition to the major disturbance, other minor perturbations also exist, such as the fluctuation of the cooling water flow rate. The fuzzy hybrid portion designed herein is employed to compensate for the effect of the major disturbance (in this respect, it is similar to a feed forward control strategy), and a second controller is required to overcome the effects of the minor disturbances. Furthermore, the fuzzy hybrid portion cannot eliminate the offset. For these two reasons, a PID feedback controller is employed in combination with this fuzzy hybrid control strategy.

For stability considerations, we have added the compensating signal before the PID controller. Figure 3 shows the structure of this fuzzy hybrid–feedback control strategy designed herein. According to the block diagram of Figure 3, the set point of the PID controller is adjusted to compensate for the effect of major disturbance. This new control structure has advantages over the traditional feed forward/feedback system. Since the fuzzy hybrid signal is used to adjust the set point of PID controller, the original fixed set point control system become a servosystem. The stability of a servosystem is the same as that of a fixed set point control system provided that the PID parameters used by moving and fixed set point systems are the same. Therefore, the hybrid control portion of this new structure does not influence the stability of the original PID control system, eliminating one of the limitations of conventional feed forward control.

In Figure 3, T_s is the set point of the system, T'_s is the set point of PID controller, and ω is a fuzzy gain that is determined by the fuzzy gain coordinator, based on the information of the major disturbance, the heat of reaction, and the first derivative of the controlled variable. From conventional feed forward control principles, we know if the disturbance is large, the output signal of feed forward controller should be "big" in fuzzy terms; if the disturbance is small, the control action should also be small, and so on. "Large," "big," and "small" are fuzzy concepts. In order to make the transient response smooth, we have divided the disturbance signal into three sections: (1) $T > T_s$ and $dT/dt \geq 0$; (2) $T > T_s$ and $dT < 0$; and (3) $T \leq T_s$. There are, therefore, nine corresponding rules inside the fuzzy gain coordinator.

In Section 1 ($T > T_s$ and $dT/dt \geq 0$),

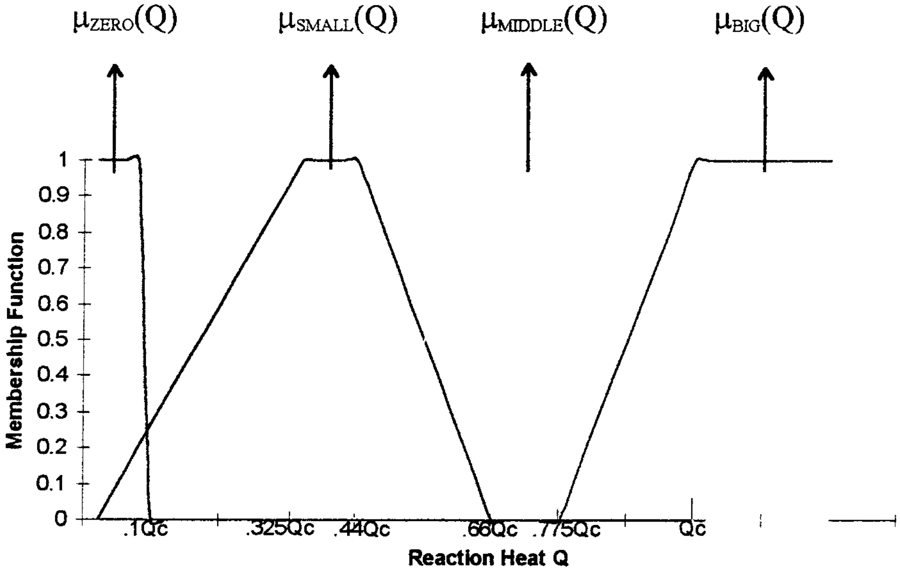

Figure 2 Fuzzy membership function of Q corresponding to the four fuzzy subsets. $Q_c = \frac{2}{3}Q_m$, where Q_m is the heat of reaction when the transient temperature response is at its maximum when controlled with a PID algorithm.

- Rule 1: If $\tilde{Q}$ is big, then the fuzzy gain ϖ is big-1;
- Rule 2: If $\tilde{Q}$ is middle, then the fuzzy gain ϖ is middle-1;
- Rule 3: If $\tilde{Q}$ is small, then the fuzzy gain ϖ is small-1;
- Rule 4: If $\tilde{Q}$ is zero, then the fuzzy gain ϖ is zero.

In Section 2 ($T > T_s$ and $dT/dt \leq 0$),

- Rule 5: If $\tilde{Q}$ is big, then the fuzzy gain ϖ is big-2;
- Rule 6: If $\tilde{Q}$ is middle, then the fuzzy gain ϖ is middle-2;
- Rule 7: If $\tilde{Q}$ is small, then the fuzzy gain ϖ is small-2;
- Rule 8: If $\tilde{Q}$ is zero, then the fuzzy gain ϖ is zero.

In Section 3 ($T \leq T_s$),

- Rule 9: The fuzzy gain ϖ is always zero

where $\tilde{Q}$ and ϖ are fuzzy variables corresponding to Q and ω; big1, middle1, and small1 are the fuzzy subsets of ω in section 1, and big2, middle2, and small2 are fuzzy subsets of ω in section 2.

From the preceding fuzzy rules, the fuzzy gain consists of the following seven fuzzy subsets: ϖ_{1} (big 1), ϖ_{2} (mid 1), ϖ_{3} (small 1), ϖ_{4} (zero), ϖ_{5} (big 2), ϖ_{6} (mid 2), and ϖ_{7} (small 2). In section 1, the reaction temperature is rising. In order to quickly reduce the temperature to the set point T_s, we assign larger fuzzy gains ($\omega_1 - \omega_3$) than in section 2, where the reaction temperature is decreasing and approaching the set point ($\omega_5 - \omega_7$). This can be represented by the following equations:

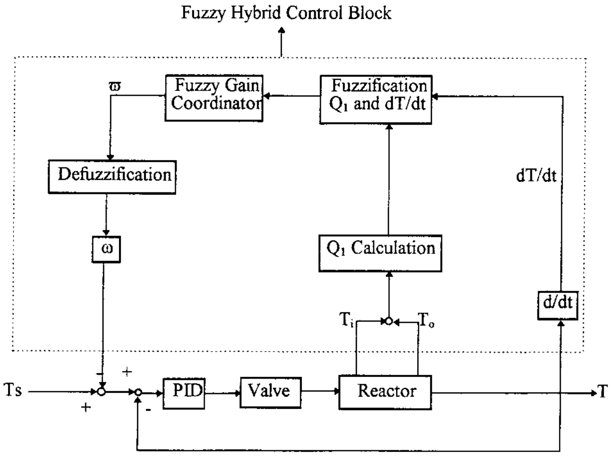

Figure 3 Block diagram of fuzzy-hybrid–PID feedback control strategy for a highly exothermic batch polymerization reactor.

$$\omega_1 = \frac{1.5(T_m - T_s)}{Q_m} \tag{5}$$

$$\omega_2 = \frac{1.2(T_m - T_s)}{Q_m} \tag{6}$$

$$\omega_3 = \frac{T_m - T_s}{Q_m} \tag{7}$$

$$\omega_4 = 0 \tag{8}$$

$$\omega_5 = \frac{0.8(T_m - T_s)}{Q_m} \tag{9}$$

$$\omega_6 = \frac{0.6(T_m - T_s)}{Q_m} \tag{10}$$

$$\omega_7 = \frac{0.4(T_m - T_s)}{Q_m} \tag{11}$$

In the preceding equations, T_m is the maximum reaction temperature in transient response controlled by a PID controller, while Q_m is the heat of reaction corresponding to the point T_m.

Defuzzification of the resulting fuzzy set is performed to obtain the maximally deterministic output by arithmetically averaging the seven output fuzzy subsets. The defuzzification formulae is

$$\omega = \frac{\Sigma\ \omega_i \mu_i}{\Sigma\ \mu_i} \tag{12}$$

where ω_i is the value corresponding to the fuzzy gain subset $\varpi_{\_i}$ (from eqs. 5–11), and μ_i is the membership function of ω belonging to the fuzzy subset $\varpi_{\_i}$ (from Fig. 2).

From the structure of this fuzzy hybrid–PID feedback control strategy and the fuzzy policy inside the fuzzy gain coordinator, it can be seen that the controller reverts to a PID feedback system when the major disturbance Q is small, the reaction temperature approaches the set point, or the reaction temperature is lower than the set point. Therefore, the main purpose of this fuzzy hybrid portion of the controller is to estimate the heat of reaction and send a signal to compensate for the effect of the major disturbance, the reaction heat, which could cause a rapid rise in temperature. The calculation of fuzzy gain ω does not depend on the process model. It depends on the features of the transient response controlled by a PID controller, T_m and Q_m, which can easily be obtained for any exothermic reactor. Therefore, this control strategy avoids reliance on a process model.

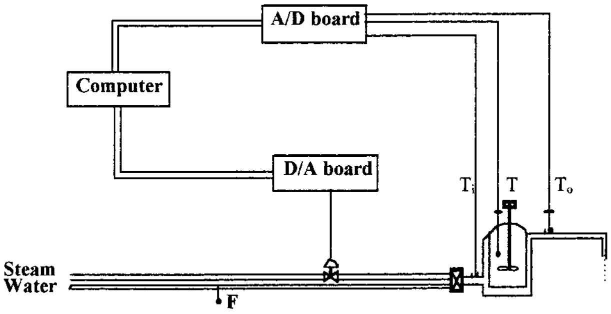

Figure 4 Schematic of the temperature control for a batch polymerization reactor.

EXPERIMENTAL

A 1-gal jacketed 316 stainless steel reactor was employed to test the fuzzy hybrid–PID feedback control strategy developed above. High pressure steam was used to adjust the temperature of inlet cooling water. The flowrate of the cooling water was fixed during the reaction as measured with a rotameter. Four residence temperature devices (RTDs) are used to detect the temperatures of the reactor, the inlet and outlet cooling water, and the water prior to the steam injection. A Macintosh computer running Labview software was used as a controller and data recorder. The control schematic is shown in Figure 4.

The polymerization of acrylamide is a highly exothermic reaction (ΔH_p = 19.5 kcal/mol).[18] It is, therefore, a good example to test the control strategy that was developed in this article. The inverse-emulsion and solution polymerizations of acrylamide have been used as two cases for the FH-PID controller. In both cases, the derivative action of the PID controller (τ_D) was set equal to zero. This was to avoid damage to the automatic valve.

Case 1: Solution Polymerization

Two hundred and twenty-five grams of solid acrylamide monomer (Cytec, Charlotte, NC) was dissolved in 3.0 L of Type I deionized water (Continental Water, San Antonio, TX. Resistivity ≥ 16.7 mΩ-cm). A chemical initiator (potassium persulfate, 99.9% pure, Fisher Scientific) was added to the reaction mixture by syringe through a septum after the solution was purged for 15 min with nitrogen (99.9% pure, AL Compressed Gas, Nashville, TN). Agitation was held constant at 400 RPM, and the set point of the reaction was 50°C. The synthesis was performed at atmosphere pres-

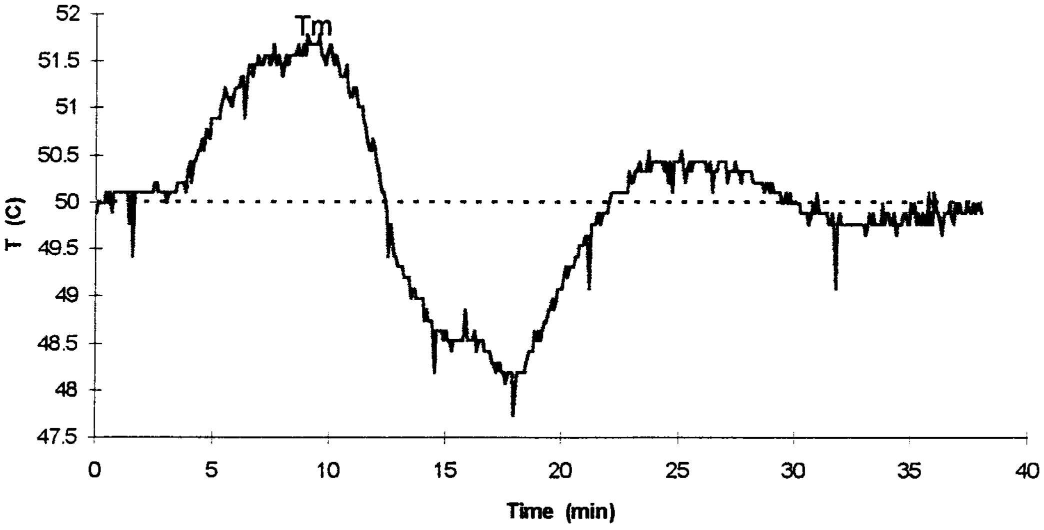

Figure 5 Transient temperature response of a batch solution polymerization of acrylamide controlled with a PI controller.

sure. The gain of the PI controller was set to 4.0, and the reset time was 100 s.

Case 2: Inverse Suspension Polymerization

Inverse-emulsion polymerization involves the dispersion of water-soluble monomer, in solution, in a continuous organic phase. Emulsifier levels are typically 2–5 wt % of the organic phase and are below the critical micelle concentration. The dispersion is thermodynamically unstable and requires both continuous vigorous agitation and the addition of a low hydrophile–lipophile-balance (HLB) steric stabilizer. Further details have been discussed by Hunkeler.[1,19]

The aqueous phase consisted of 703.4 g of acrylamide crystal in 1307.3 g of deionized water. The organic phase was comprised of 900.0 g of Isopar-M (Exxon, supplied by ChemCentral, Nashville, TN; a narrow cut of isoparaffinic with properties similar to decane and a boiling point between 220 to 240°C with less than 2% aromatics). A block copolymeric steric stabilizer, HB239 (ICI Americas, Wilmington, DE), was used as an emulsifier at a level of 3.3 wt % (100.0 g).[20] Both phases were independently sparged with N_2 for 15 min

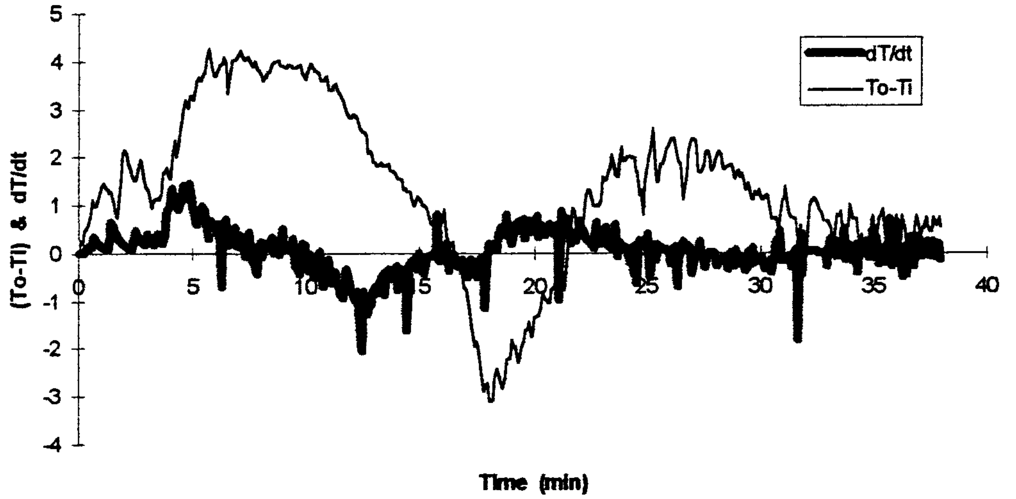

Figure 6 The dynamic signals of ΔT and dT/dt during the transient process of a batch solution polymerization of acrylamide controlled with a PI controller.

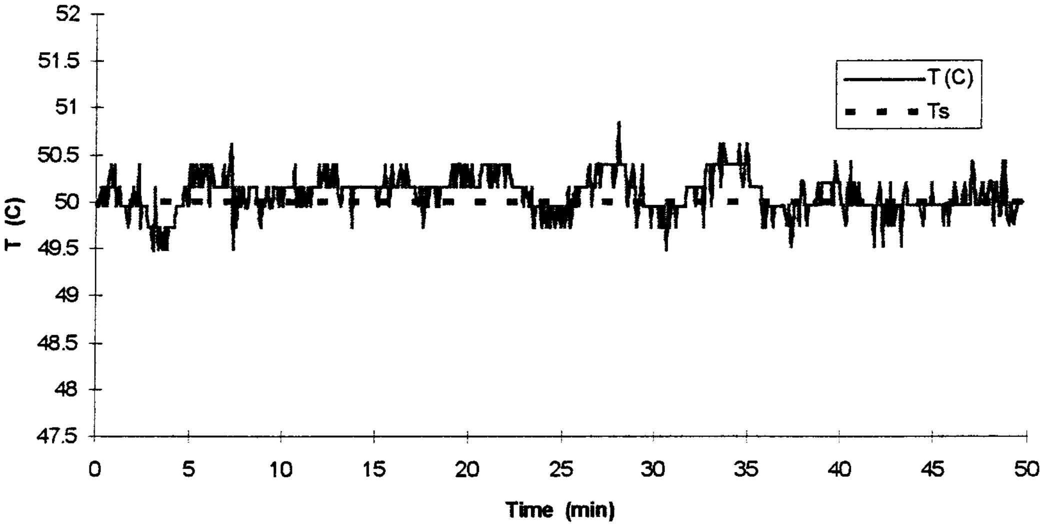

Figure 7 Transient temperature response of a batch solution polymerization of acrylamide controlled with a FH-PI controller.

prior to combination and then for another 15 min while under agitation (400 RPM). Azobisisobutyronitrile (Eastman Kodak, Rochester, NY; 99.9% pure) was used as an oil soluble initiator and was injected in 20 mL of acetone via a syringe through a septum. The set point of the reaction was 50°C, and the polymerization was carried out at atmospheric pressure using the same PI tuning constants as at case 1.

For both solution and inverse-emulsion polymerizations, the reaction did not proceed, as was determined by gravimetric analysis, prior to the injection of the initiator. Aliquots were periodically withdrawn from the bottom of the reactor with presterilized 20 mL glass scintillation vials (Fisher Scientific), which contained 100 ppm hydroquinone to terminate the reaction.

RESULTS AND DISCUSSION

Figure 5 shows the transient temperature response of the solution polymerization (case 1) controlled by the conventional PID method. Deviations of over 2°C are observed. Figure 6 shows the dynamic signals of ΔT and dT/dt during the

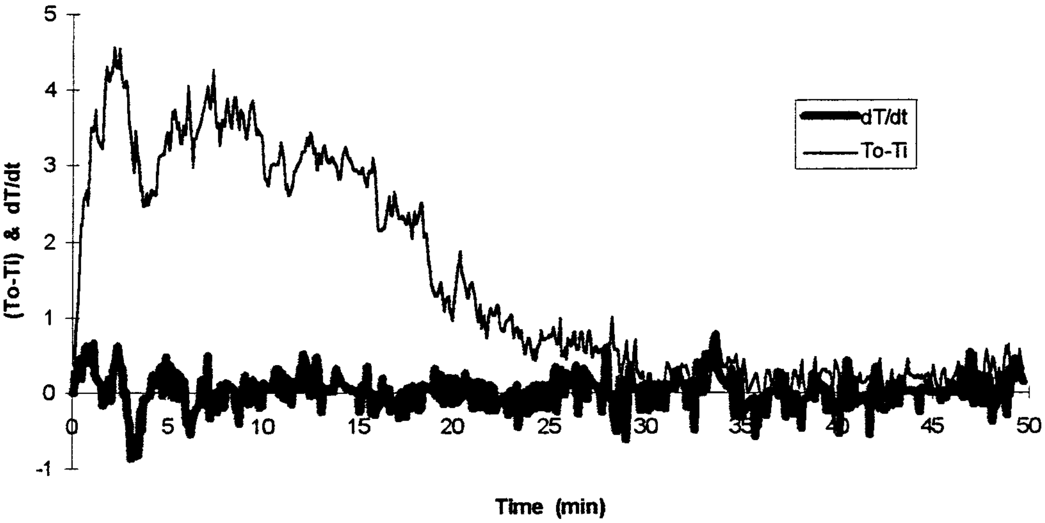

Figure 8 Dynamic signals of ΔT and dT/dt during the transient process of a batch solution polymerization of acrylamide with a FH-PID controller.

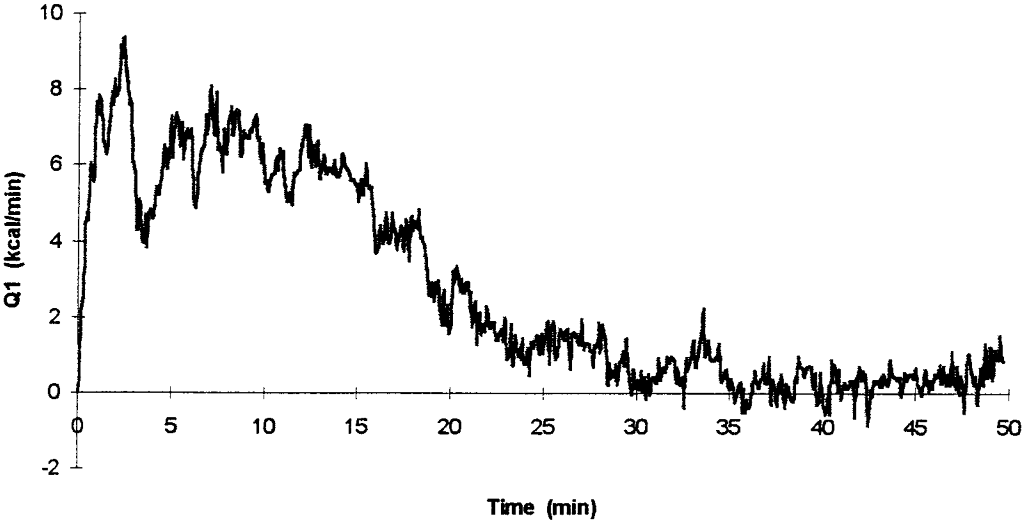

Figure 9 The normalized heat of reaction (Q) during a batch solution polymerization controlled with a FH-PID controller.

reaction controlled by the PID controller. From Figure 5, we can determine the maximum temperature in the transient response (T_m = 51.75°C). The corresponding heat of reaction (Q_m = 8.4 kcal/min) can be calculated for the solution polymerization system from Figure 6. These two pa-

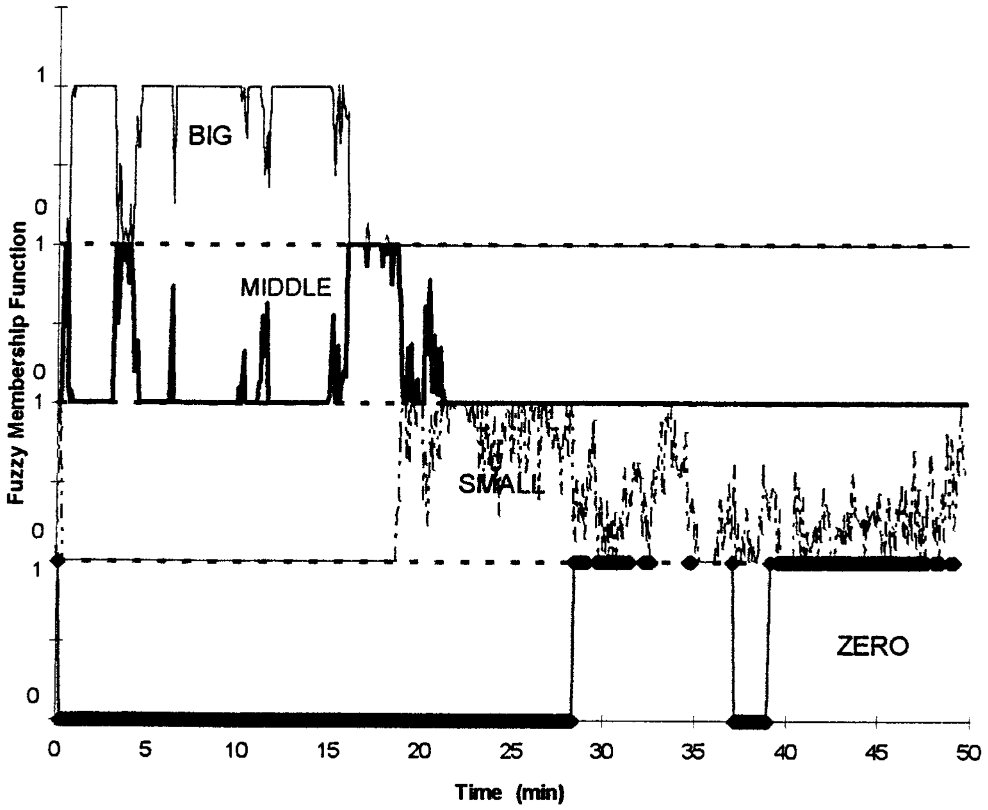

Figure 10 Fuzzy membership functions of the reaction heat belonging to the four fuzzy subsets during the batch solution polymerization controlled by the FH-PID controller.

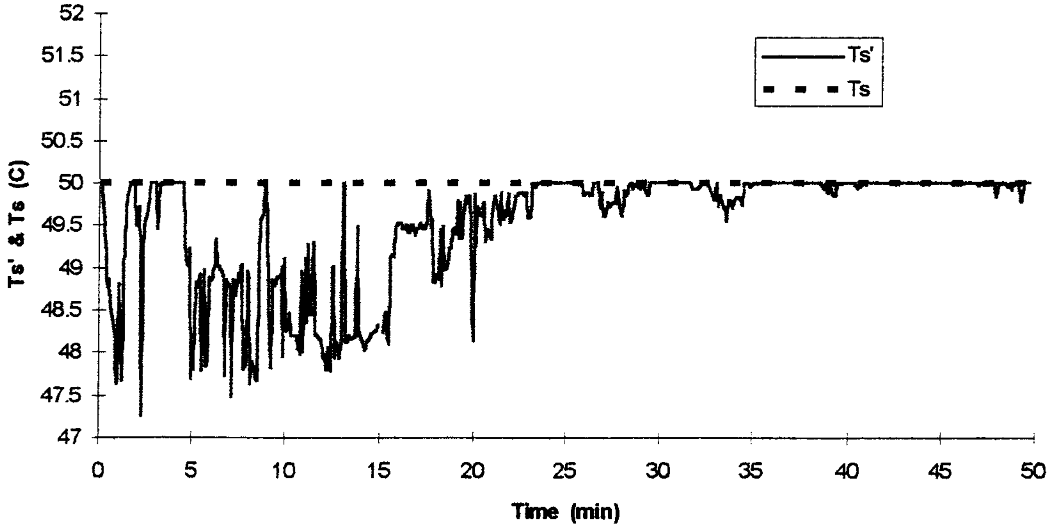

Figure 11 Setpoint of the PID controller (T_s') profile during the batch solution polymerization.

rameters will be used in the FH-PID controller for the temperature control of this batch solution polymerization reactor. Figure 7 shows the reaction temperature response controlled by the FH-PID controller. A maximum deviation of less than 1°C is observed. Figure 8 shows the dynamic signals of ΔT and dT/dt during the transient process controlled with a FH-PID controller. Figure 9 shows the normalized heat of reaction (Q_1) during the transient process. The parameter Q_m was used to create a fuzzy membership function for this system. The fuzzy value of the reaction heat was obtained from Figure 9 and the created fuzzy membership functions. Figure 10 shows the membership functions of the reaction heat corresponding to the four fuzzy subsets during the batch solution polymerization controlled by the FH-PID controller. From Figure 10, it can be seen that the heat of reaction primarily belonged to the "big" fuzzy subset at the initial period ($t < 15$ min). The heat of reaction then decreased to middle during the intermediate period of the reaction (15 to 22 min) and declined to small and zero during the final stages of the polymerization. Based on the

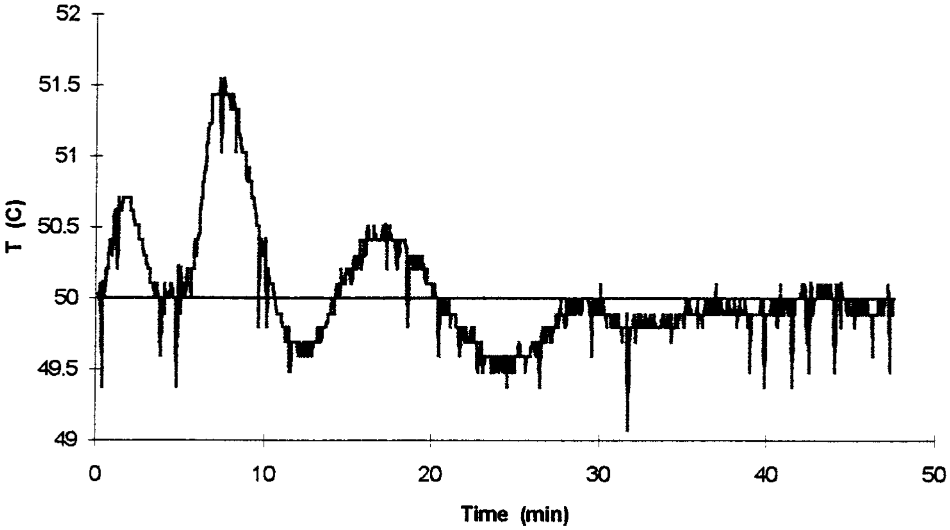

Figure 12 Transient temperature response of a batch inverse-emulsion polymerization of acrylamide controlled with a PI controller.

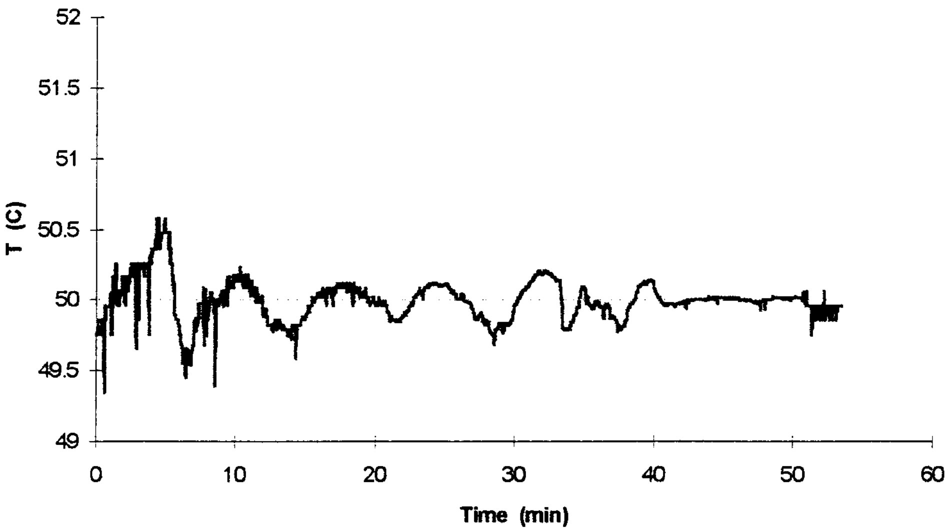

Figure 13 Transient temperature response of a batch inverse-emulsion polymerization of acrylamide controlled with a FH-PI controller.

dynamic behavior controlled by the FH-PID controller and fuzzy value of the heat generation, the fuzzy hybrid outputs were calculated to adjust the set point of PID controller during polymerization. Figure 11 shows the profile of the set point of PID controller during batch polymerization process. T_s' was lowered during the initial maximum rate period in order to quickly reduce the overshoot. Figures 8 to 11 illustrate the workings of this FH-PID controller. Comparing the transient responses controlled by PID controller (Fig. 5) and FH-PID controller (Fig. 7), it is obvious that the performance of FH-PID is much superior to that of PID controller. The control of heterophase water-in-oil acrylamide polymerizations has been a challenging commercial and academic concern for over two decades. The development of FH-PID strategies that can reduce the reliance on "air stops" oxygen additions to kill runaway polymerizations by scavenging radicals,[21] as is common in industry, is likely to lead to water soluble polymers with improved performance as flocculants.

Figures 12 and 13 show the transient temperature responses of an inverse-emulsion polymerization of acrylamide respectively controlled with PID controller and FH-PID controllers, respectively. The temperature overshoot with a FH-PID controller was 0.5°C, compared to 1.5°C with the PID controller in isolation. This represents only the second demonstration[22] of an isothermal inverse-microemulsion-like system in the literature, and the low overshoot will be associated with a more uniform molecular weight distribution. Clearly, in neither case presented herein is the PI controller optimally tuned. However, we have in another article[23] shown that the fuzzy hybrid portion of the controller improves the control properties independent of the degree of tuning of the PI block. That is, even if the PI provides very precise temperature control, the fuzzy controller reduces the overshoot and the settling time.

CONCLUSIONS

In this article the design process for a FH-PID controller has been described and the performance of a FH-PID controller tested on a pilot batch polymerization reactor. The fuzzy hybrid control block utilizes a fuzzy model to estimate the major disturbance and adjust the set point of conventional PID feedback controller. In this way, the hybrid block will not adversely influence the stability of the original PID control system. Furthermore, the parameters in the hybrid block do not depend on a process mathematical model, which provides an advantage over the conventional model based control strategies, such as feed forward control and adaptive control. The new structure for hybrid–feedback controllers has been shown to improve the stability of a highly exothermic nonlinear polymerization process and serves as a robust tool, particularly for non-commodity polymers, for which detailed mechanistic and kinetic information may not be available. This method is, however, general and is recommended for any polymerization in which the exotherm is nonuniform with conversion, including systems with severe autoacceleration.

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