OUTPUT-FEEDBACK CONTROL OF CONTINUOUS POLYMER REACTORS WITH CONTINUOUS AND DISCRETE MEASUREMENTS

Pablo González and Jesús Alvarez

Universidad Autónoma Metropolitana-Iztapalapa
Depto. de Ingeniería de Procesos e Hidráulica
Apdo. 55534, 09340 México D.F, MÉXICO

Abstract: An output-feedback (OF) control to stabilize continuous free-radical solution polymer reactors is presented, on the basis of continuous measurements of temperatures, level and flows, and discrete-delayed measurements of molecular-weight (MW). First, the state-feedback controller is presented, and its behavior is the recovery target for the OF design. The OF control consists of continuous linear PI-type decentralized volume and cascade temperature controllers, a continuous material-balance monomer controller, and a discrete MW controller. The temperature controller requires two approximate static parameters, the monomer controller requires the heat capacity function, and the MW controller requires one static parameter and initiation constants (pre-exponential factor and activation energy), which are fewer modeling requirements than the ones of the case without MW measurements. The proposed control technique has a systematic construction and simple tuning guidelines, and is tested with an industrial size reactor through simulations. *Copyright © 2006 IFAC*

Keywords: Polymerization reactor control, decentralized control, discrete measurements, discrete estimator, chemical process control, continuous process control.

1. INTRODUCTION

In the last two decades the polymerization reactor problem has been the subject of extensive theoretical, simulation and experimental studies, given the demand of processes with better compromises between safety, productivity and quality, and the development of control methods. In a typical industrial setting, the volume and temperature are controlled with decentralized linear PI controllers, and the conversion and molecular weight (MW) are feedback and/or feedforward controlled with inferential, advisory, or supervisory control schemes. On the other hand, in the academic field a diversity of control techniques have been employed, such as nonlinear geometric (Soroush and Kravaris, 1993; Alvarez, 1996; Gauthier and Kupka, 2001), MPC (Mutha et al., 1997), and calorimetric (Alvarez et al., 2004) control techniques; these controllers have been implemented with open-loop (Soroush and Kravaris, 1993), extended Kalman filter (EKF) (Mutha et al, 1997), and Luenberger (Alvarez, 1996; Gauthier and Kupka, 2001) nonlinear observers. Despite valuable insight has been gained in the understanding of the polymer reactor control problem, the resulting nonlinear controllers are strongly interactive and model dependent, signifying complexity and reliability drawbacks for industrial applicability.

Recently, González and Alvarez (2005) presented a PI-inventory controller which: (i) combines the simplicity features (linearity, decentralization, and modeling dependency) of the PI and inventory industrial controllers (Shinskey, 1988; Luyben, 1990) with the structure and robustness design tools offered by the nonlinear geometric (Isidori, 1995) and constructive (Sepulchre et al., 1997) control approaches, (ii) recovers the behavior of an exact model-based nonlinear state-feedback (SF) passive controller, (iii) employs continuous-instantaneous (CI) measurements of volume, temperatures and flows, (iv) doubles the molecular-weight (MW) response speed in comparison with the MW open-loop mode, and (v) regulates the MW with an offset whose size depends on the accuracy of the initiation rate and transfer models.

These observations rise the issue that constitutes the motivation of the present work: the incorporation of discrete-delayed (DD) MW measurements to speed-up the response and eliminate the asymptotic offset of the MW output.

In this work, an output-feedback (OF) controller to regulate a (possibly open-loop unstable) polymerization reactor is presented, on the basis of: (i) continuous level, temperature and flow measurements, (ii) discrete-delayed MW measurements, and (iii) mass-energy balances. For applicability purposes, the quest of linearity, decentralization and reduced model dependency features as well as the derivation of conventional-like tuning guidelines are important design objectives.

2. CONTROL PROBLEM

Consider a CSTR where an exothermic free-radical solution homopolymer reaction takes place. Monomer, solvent and initiator are fed to the tank, and heat exchange is enabled by a cooling jacket. Due to the gel effect (Chiu et al, 1983), the reactor can have multiple steady-states (Hamer et al., 1981). From standard free-radical polymerization kinetics (Hamer et al., 1981), and viscous heat exchange considerations (Alvarez et al., 1996), the reactor dynamics are given by the following energy and material balances:

$$\dot{T} = \{\Delta r - U(T - T_j) + (\rho_m q_m c_m + \rho_s q_s c_s)(T_e - T)\}/C := f_T, \qquad y_T(t) = T \qquad (1a)$$

$$\dot{T}_j = \{U(T - T_j) + \rho_j q_j c_j (T_{je} - T_j)\}/C_J := f_j, \qquad y_j(t) = T_j \qquad (1b)$$

$$\dot{V} = q_m + q_s - (\varepsilon_m/\rho_m)\, r - q := f_V, \;\; y_V(t) = V \qquad (1c)$$

$$\dot{m} = - r + \rho_m q_m - (m/V)\, q := f_m \qquad (1d)$$

$$\dot{\pi} = (r - \pi\, r_0)\pi/(V\rho - m - s) := f_\pi, \;\; y_\pi(t_k) = \pi(t_{k-1}) \qquad (1e)$$

$$\dot{I} = - r_i + w_i - (I/V)\, q := f_i \qquad (1f)$$

$$\dot{s} = \rho_s q_s - (s/V)\, q := f_s \qquad (1g)$$

$$\dot{\mu}_2 = r_2 - (\mu_2/V)\, q := f_{\mu 2} \qquad (1h)$$

$$z_T = T,\; z_V = V,\; z_m = m,\; z_\pi = \pi$$

$$u_j = q_j,\; u_V = q,\; u_m = q_m,\; u_i = w_i$$

$$r = f_r(T, V, m, I, s), \qquad Q = \Delta\, r \qquad (2a)$$

$$U = f_U(T, T_j, V, m, s), \qquad H = U(T - T_j) \qquad (2b)$$

$$C = f_C(V, m, s), \qquad \rho = f_\rho(V, m, s) \qquad (2c)$$

$$r_i = f_{ri}(T, I), \quad (r_0, r_2)' = (f_0, f_2)'(T, V, m, I, s) \qquad (2d, e)$$

$$\theta = W_m \mu_2/[(V\rho - m - s)\pi] \qquad (2f)$$

The *states* (x) are: the reactor (T) and jacket (T_j) temperatures, the volume (V), the free (i.e., unreacted) monomer (m), solvent (s) and initiator (I) masses, as well as the (number-average) molecular weight (π) and second moment (μ_2) of the MW distribution. The *measured exogenous inputs* (d) are: the reactor (T_e) and jacket (T_{je}) feed temperatures, and the solvent (q_s) volumetric flowrate. The *regulated outputs* (z) are: the temperature (T), the volume (V), the monomer content (m), and the (number-average) molecular weight (π). The *continuous-instantaneous measured outputs* (y_c) are: the temperature (y_T), the volume (y_V), and the jacket temperature (y_j). The *discrete-delayed measured output* (y_d) is the molecular weight (y_π). The *control inputs* (u) are: the coolant volumetric flowrate (q_j) through the jacket circuit, the exit flowrate (q), the monomer flowrate (q_m) and the initiator mass feedrate (w_i). Δ is the heat of polymerization per unit monomer mass, W_m is the monomer molecular weight, ε_m is the monomer contraction factor, ρ_m (or c_m), ρ_s (or c_s) and ρ_j (or c_j) are the monomer, solvent and coolant fluid densities (or specific heat capacities), C and C_J are the reacting mixture and cooling system heat capacities; U, ρ, r, r_i, r_0, and r_2 are the heat transfer coefficient, the reacting mixture density and the rates of polymerization, initiator decomposition, and change of the zeroth and second moments (Hamer et al., 1981); θ is the MW polydispersity. The moment rates r_0 and r_2 can be expressed in terms of initiation and monomer and solvent transfer rates (Flory, 1953).

In vector notation, the reactor model (1) is given by:

$$\dot{x} = f(x, d, u), \qquad y = C_y x, \qquad z = C_z x \qquad (3)$$

$$x = (T, T_j, V, m, \pi, I, s, \mu_2)'$$

$$f = (f_T, f_j, f_V, f_m, f_\pi, f_i, f_s, f_2)', \quad d = (T_e, T_{je}, q_s)'$$

$$y = (y_c', y_d)', \qquad y_c = (y_T, y_j, y_V)', \qquad y_d = (y_\pi)$$

$$u = (q_j, q, q_m, w_i)', \; z = (z_T, z_V, z_m, z_\pi)'$$

In a previous study (González and Alvarez, 2005), the behavior of an exact model-based MIMO nonlinear passive SF controller was recovered by means of a measurement-driven controller with: linear-decentralized volume and cascade temperature PI-controllers, as well as feedforward-like monomer and MW controllers. Having this study as a point of departure, in this work is addressed the case of controlling the (possibly open-loop unstable) reactor (3) with DD MW measurements. In particular, we are interested in redesigning the nonlinear MW control component of the abovementioned study (González and Alvarez, 2005): (i) in the light of the linearity, decentralization and reduced model dependency features that underlie the functioning of the CI measurement-driven volume and temperature PI components, and (ii) with conventional-like tuning guidelines that account for the DD nature of the MW measurement.

3. BEHAVIOR RECOVERY TARGET

From the development of a previous work (González and Alvarez, 2005), in this section an exact model-based nonlinear SF passive controller is presented, whose behavior is the recovery target of the proposed OF controller. Since the following solvability conditions

$$\text{(i) } f_U > (T_j - T)\partial_{T_j} f_U, \qquad \text{(ii) } V f_\rho > m + s \qquad (4)$$

(iii) $\partial_I f_r > \pi\, \partial_I f_0$

(iv) Stable (solvent- MW second moment) zero-dynamics: $\dot{x}_I = \phi_I(x_I, d), \quad x_I(0) = x_{Io}$

are met by the reactor class (4), the *cascade (passive) SF controller*

$$u_p = \eta_p(x, d, K_p, p), \qquad u_p = (q, q_m)' \qquad (5a)$$

$$u_s = \eta_s(x, d, \dot{d}, K_s, p), \qquad u_s = (q_j, w_i)' \qquad (5b)$$

yields a closed-loop stable operation. Here, u_p (or u_s) is the primary (or secondary) controller, K_p (or K_s) is the primary (or secondary) control gain matrix, and η_p, η_s, and ϕ_I are nonlinear maps (defined in González and Alvarez, 2005) determined by the kinetics (f_r, f_0), heat exchange (f_U), and heat capacity (f_C) functions (2) as well as some of their partial derivatives. The regulated outputs (z) converge to their nominal values as with adjustable rates (k_V, k_T, k_m, k_π):

$$z_V(t) \xrightarrow{\sim k_V} \bar{z}_V, \qquad z_T(t) \xrightarrow{\sim k_T} \bar{z}_T \qquad (6a, b)$$

$$z_m(t) \xrightarrow{\sim k_m} \bar{z}_m, \qquad z_\pi(t) \xrightarrow{\sim k_V} \bar{z}_\pi \qquad (6c, d)$$

The last controller (5) sets the limiting behavior (6) attainable by feedback control with maximum robustness and LNPA output dynamics, and such behavior is regarded as the recovery target for the development of the related measurement-driven controller.

4. OUTPUT-FEEDBACK CONTROL

As shown in our previous study (González and Alvarez, 2005), the direct (Luenberger or EKF) estimator-based implementation of the preceding nonlinear passive SF controller (5) is unduly complex and modeling dependent, and the same control task can be performed, in a simpler way, by means of a combination of (volume and temperature) PI decentralized feedback controllers with monomer and MW material-balance-based feedforward components that require initiation and transfer function models (2d, e). Since we are looking at a MW control redesign given the availability of DD MW measurements and the quest of linearity, decentralization and model independency features, let us recall the control model employed in the abovementioned study (González and Alvarez, 2005), now with DD MW measurements:

$$\dot{V} = b_V - q, \qquad y_V(t) = V \qquad (7a)$$

$$\dot{T} = a_T T_j + b_T, \qquad y_T(t) = T \qquad (7b)$$

$$\dot{T}_j = a_j q_j + b_j, \qquad y_j(t) = T_j \qquad (7c)$$

$$\dot{\pi} = a_\pi I + b_\pi, \qquad y_\pi(t_k) = \pi(t_{k-1}) \qquad (7d)$$

$$\dot{I}^* = v_i^*, \qquad y_i^*(t_k) = I^*(t_k) \qquad (7e)$$

$$(b_V, b_T, b_j, b_\pi)' = \beta(x, d, u, p) \qquad (7f)$$

where the nonlinear maps (b_V, b_T, b_j) and the static parameters (a_T, a_j) are defined by González and Alvarez (2005), and (a_π, b_π) are given by

$$a_\pi = -\,2\,\bar{\pi}^2\, \hat{f}_d\, \hat{k}_{d0} e^{-Ed/RT}/[\bar{V} f_\rho(\bar{V}, \bar{m}, \bar{s}) - \bar{m} - \bar{s}]$$

$$b_\pi = \{\pi f_r(T, V, m, I, s) - V\pi^2\kappa(T, m, s) - 2\,\pi^2 f_d\, f_{r_I}(T, I)\}/[V f_\rho(V, m, s) - m - s] - a_\pi I$$

Equation (7a-d) [or (7f)] is a linear-decentralized dynamic (or nonlinear, interactive and static) component, and (7) is an (exact) b-parametric representation of the actual reactor model (1). I^* is the initiator content regarded as a "virtual control input" in a cascade configuration, and $\dot{I}^* = v_i^*$ is its time derivative. The MW measurement (y_π) available at k-th time (t_k) is the value of the MW sampled at the time t_{k-1}. In other words, the MW measurement involves a delay of one sampling period.

Observe that b_V, b_T, b_V, and b_π are unknown inputs that are determined by the measurements (u, y, $\dot{y}$), and consequently, can be quickly reconstructed by means of a set of linear, decentralized observers, one for each (b_i-y_i) pair. Since the construction of the CI measurements-based observers and their corresponding feedback controllers are given in a previous study (González and Alvarez, 2005), here it suffices to address the development of a suitable discrete observer for the MW measurement and the construction of the related controller.

4.1 MW estimator

To handle the DD nature of the MW measurement, a discrete state estimator must be employed, and the load disturbance b_π (8) can be estimated from the DD MW measurement (y_π) in conjunction with the MW balance (7d). To construct the discrete estimator, let us make the standard estimation assumptions $\dot{b}_\pi \approx 0$, $\dot{v}_i^* \approx 0$, and write the Euler discrete version of these equations in conjunction with the discrete approximations of the MW balance (7d) and the initiator set point derivative (7e), and obtain the discrete model of the MW balance and of the initiator set point filter:

$$\pi(t_k) = \pi(t_{k-1}) + [a_\pi I(t_{k-1}) + b_\pi(t_{k-1})]\,\delta \qquad (8a)$$

$$b_\pi(t_k) = b_\pi(t_{k-1}) \qquad y_\pi(t_k) = \pi(t_{k-1}) \qquad (8b)$$

$$I^*(t_{k+1}) = I^*(t_k) + v_i^*(t_k)\,\delta \quad (9a)$$
$$v_i^*(t_{k+1}) = v_i^*(t_k) \qquad y_i^*(t_k) = I^*(t_k) \quad (9b)$$

The application of the geometric discrete estimation technique (Hernández and Alvarez, 2003) yields the MW estimator (10) and initiator setpoint filter (11):

$$\hat{\pi}(t_k) = \hat{\pi}(t_{k-1}) + [a_\pi \hat{I}(t_{k-1}) + \hat{b}_\pi(t_{k-1})]\,\delta + k_{D_1}[y_\pi(t_k) - \hat{\pi}(t_{k-1})] \quad (10a)$$
$$\hat{b}_\pi(t_k) = \hat{b}_\pi(t_{k-1}) + k_{D_2}[y_\pi(t_k) - \hat{\pi}(t_{k-1})] \quad (10b)$$
$$\hat{I}^*(t_{k+1}) = \hat{I}^*(t_k) + \hat{v}_i^*(t_k)\,\delta + k_{D_1}[y_i^*(t_k) - \hat{I}^*(t_k)] \quad (11a)$$
$$\hat{v}_i^*(t_{k+1}) = \hat{v}_i^*(t_k) + k_{D_2}[y_i^*(t_k) - \hat{I}^*(t_k)] \quad (11b)$$

where the (k_{D_1}, k_{D_2}) are the discrete estimator gains according to the following expressions

$$k_{D_1} = 2 - 2\,e^{-\zeta\omega\delta}\cos[\omega\delta(1 - \zeta^2)^{1/2}], \qquad \delta = t_k - t_{k-1}$$
$$k_{D_2}(\zeta, \omega, \delta) = 1 + e^{-2\zeta\omega\delta} - 2\,e^{-\zeta\omega\delta}\cos[\omega\delta(1 - \zeta^2)^{1/2}]$$

δ is the sampling period, and ω (or ζ) is the characteristic frequency (or damping factor) associated to the mappings of the estimator design poles into the continuous representation in the LHS of the complex plane (Hernández and Alvarez, 2003).
Observe that, due to the discrete nature of the MW (8) and initiator setpoint (9) models and the DD feature of the MW measurement: (i) the initiator setpoint filter (11) is a one-step-ahead predictor, and (ii) the MW estimator (10) yields the present estimate on the basis of the actual MW value one-step-behind.

4.2 MW SF controller

Recall the discrete MW balance (8a), regard the initiator content (I) as a virtual controller (I^*), impose the closed-loop discrete dynamics (with gain k_π) for the MW, this is,

$$a_\pi I^*(t_k) + b_\pi(t_k)] = - k_\pi[\pi(t_k) - \bar{z}_\pi]$$

solve this equation for I^* to obtain the primary MW SF controller (12a), and combine this primary controller with the initiator balance (1f) to obtain the secondary controller (12b). Thus, the result is the *cascade MW SF controller*

$$I^*(t_k) = \{b_\pi(t_k) + k_\pi[\pi(t_k) - \bar{z}_\pi]\}/a_\pi \quad (12a)$$
$$w_i = v_i^*(t_{k+1}) + f_{ri}[T, I^*(t_k)] + [I^*(t_k)/V]q \quad (12b)$$

driven by discrete $[\pi(t_k)]$ and continuous (V, T, q) measurements.

4.3 Output-feedback reactor controller

The combination of the MW SF controller (12) with the MW estimator (10) and initiator setpoint filter (11) yields our DD MW measurement-driven controller (13c), and the volume, temperature and monomer controllers are the ones presented in a previous study. Thus, the entire *OF reactor controller* is given by:

Volume and temperature controllers (13a)

$$\dot{\hat{V}} = \hat{b}_V - q + 2\zeta\omega(y_V - \hat{V}), \qquad \dot{\hat{b}}_V = \omega^2(y_V - \hat{V})$$
$$\dot{\hat{T}} = a_T\hat{T}_j + \hat{b}_T + 2\zeta\omega(y_T - \hat{T}), \qquad \dot{\hat{b}}_T = \omega^2(y_T - \hat{T})$$
$$\dot{\hat{T}}_j = a_j q_j + \hat{b}_j + 2\zeta\omega(y_j - \hat{T}_j), \qquad \dot{\hat{b}}_j = \omega^2(y_j - \hat{T}_j)$$
$$q = \hat{b}_V + k_V(\hat{V} - \bar{z}_V)$$
$$T_j^* = - [(\hat{b}_T + k_T(\hat{T} - \bar{z}_T)]/a_T$$
$$\dot{T}_j^* = - \{\omega^2(y_T - \hat{T}) + k_T[a_T\hat{T}_j + \hat{b}_T + 2\zeta\omega(y_T - \hat{T})]\}/a_T$$
$$q_j = [\dot{T}_j^* - \hat{b}_j - k_j(\hat{T}_j - T_j^*)]/a_j$$

Monomer controller (13b)

$$\dot{\hat{m}} = - \hat{r} + \rho_m q_m - (\hat{m}/\hat{V})\,q, \qquad \dot{\hat{s}} = \rho_s q_s - (\hat{s}/\hat{V})\,q$$
$$\hat{r} = [f_C(\hat{V},\hat{m},\hat{s})(a_T\hat{T}_j + \hat{b}_T) + C_j\hat{b}_j)]/\Delta$$
$$q_m = [- k_m(\hat{m} - \bar{z}_m) + \hat{r} + (\hat{m}/\hat{V})\,q]/\rho_m$$

MW controller (13c)

$$\dot{\hat{I}} = - f_{ri}(\hat{T}, \hat{I}) + w_i - (\hat{I}/\hat{V})\,q$$
$$\hat{\pi}(t_k) = \hat{\pi}(t_{k-1}) + [a_\pi\hat{I}(t_{k-1}) + \hat{b}_\pi(t_{k-1})]\,\delta + k_{D_1}[y_\pi(t_k) - \hat{\pi}(t_{k-1})]$$
$$\hat{b}_\pi(t_k) = \hat{b}_\pi(t_{k-1}) + k_{D_2}[y_\pi(t_k) - \hat{\pi}(t_{k-1})]$$
$$\hat{I}^*(t_{k+1}) = \hat{I}^*(t_k) + \hat{v}_i^*(t_k)\,\delta + k_{D_1}[y_i^*(t_k) - \hat{I}^*(t_k)]$$
$$\hat{v}_i^*(t_{k+1}) = \hat{v}_i^*(t_k) + k_{D_2}[y_i^*(t_k) - \hat{I}^*(t_k)]$$
$$I^*(t_k) = \{\hat{b}_\pi(t_k) + k_\pi[\hat{\pi}(t_k) - \bar{z}_\pi]\}/a_\pi$$
$$w_i(t_k) = \hat{v}_i^*(t_{k+1}) + f_{ri}[\hat{T}, \hat{I}^*(t_k)] + [\hat{I}^*(t_k)/\hat{V}]\,q$$

This OF controller (13) consists of linear PI-type decentralized volume and cascade temperature controllers (13a), linear and decentralized cascade MW controller (13c), and a material-balance monomer controller (13b). Comparing with the case without MW measurements (González and Alvarez, 2005), the OF controller (13) has: (i) a linear discrete estimator with MW measurements (10), coordinated with a linear discrete estimator (11) for the initiator set point (I^*), and (ii) an initiator feedrate input (12b) from a material balance, without feedback term. The discrete estimator (10) replaces the continuous MW estimator without MW injection of the abovementioned work, and has fewer modeling requirements.

Model requirements. The modeling requirements of the proposed OF controller (13) are the following: (i) the temperature controller requires two approximate static parameters (a_T, a_j), (ii) the MW controller requires one static parameter (a_π) and initiation constants [pre-exponential factor and activation energy in the function f_{ri} of (12b)], and (iii) the monomer controller requires the heat capacity function (f_C) and the related calorimetric parameters.

Comparing with the modeling requirements of the case without MW measurements (González and Alvarez, 2005), the proposed controller (13) does not need the transfer function model, and this is so because of the DD MW measurement introduced in the primary control part. On the other hand, these modeling requirements are considerably smaller than the ones of the estimator-based nonlinear controllers employed in previous polymer reactor studies (Soroush and Kravaris, 1993; Alvarez, 1996; Mutha et al., 1997; Gauthier and Kupka, 2001).

Closed-loop dynamics and tuning. The rigorous assessment of the robust closed-loop behavior goes beyond the scope of the present work, and here it suffices to state that: (i) such assessment can be performed with a suitable extension (Hernández and Alvarez, 2003) of the nonlocal input-to-state stability framework employed in the case without MW measurements (González and Alvarez, 2005), and (ii) the related tuning guidelines amount to the ones given in the last work for the CI measurements and to the ones given by Hernández and Alvarez (2003) for a discrete estimator. Next are given the tuning guidelines for the present case:

1. Choose the sampling period δ (equal to the measurement delay) to be from 1/10th to 1/20th of reactor residence time, according to the well known sampling theorem-based criterion (Stephanopoulos, 1984) employed in control designs.
2. Set the MW control gain at the inverse of the nominal residence time, $k_\pi = 1/\tau_R$ and set the estimator frequency parameter (ω) about three times faster, $\omega = 3/\tau_R$.
3. Increase the estimator parameter ω up to its ultimate value ω^+, where the response becomes oscillatory, and backoff until a satisfactory response is attained, say at $\omega \leq \omega^+/3$.
4. Increase the MW gain k_π up to its ultimate value k_π^+, and then back off until a satisfactory response is attained, say $k_\pi \leq k_\pi^+/3$.

This tuning should yield a closed-loop stable reactor where the discrete-delayed measured MW is regulated asymptotically with almost linear error dynamics and adjustable convergence rate, depending on modeling errors, measurement noise, measurements sampling period and delay, and natural reactor dynamics.

5. APPLICATION EXAMPLE

To subject the OF controller to an extreme industrial situation, let us consider (via numerical simulations) the operation of a reactor about an open-loop unstable steady-state, at high-solid fraction with the potentially destabilizing gel-effect at play. The system is methyl methacrylate (monomer)-ethyl acetate (solvent)-AIBN (initiator). The residence time is τ_R = 220 minutes with a nominal volume $\bar{z}_V \approx$ 2000 L. The operating conditions are given by González and Alvarez (2005), and the reactor has three steady states $\bar{x} = [\bar{T}(K), \bar{m}(Kg), \bar{\pi}(Kg/Kmol)]'$:

$\bar{x}_1$: (373.88, 312.7, 29395.15)'

$\bar{x}_2$: (351.62, 660.1, 110384.75)'

$\bar{x}_3$: (329.72, 1361.1, 399149.03)'

The second steady-state ($\bar{x}_2$) is open-loop unstable and was chosen as the control setpoint. Following the tuning guidelines of section 4 and the ones from González and Alvarez (2005), the observer and control gains were set as follows:

δ = 15 min, ζ = 0.71, $\omega = (1/5)\ \mathrm{min}^{-1}$
$k_j = k_V = \omega/4$, $k_T = k_\pi = \omega/8$, $k_m = 1/\tau_R$

with a MW sampling period (δ) that is feasible according to experimental works (Mutha et al., 1997), and an observer damping factor (ζ) that was set according to a Butterworth criterion (Alvarez and López, 1999).

In Fig. 1, three closed-loop responses are shown with (i) the cascade SF controller (5), (ii) the proposed OF controller (13) with CI and DD measurements, and (iii) the proposed OF controller with CI and DD measurements and a typical - 20 % error in the frequency factor (k_{d0}) of the initiation rate.

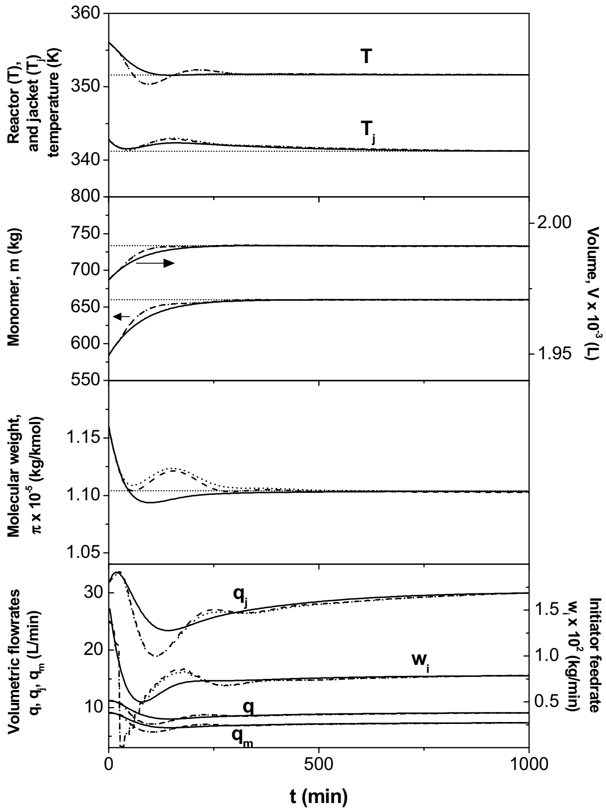

Fig. 1. Reactor behavior with the model-based cascade SF control (——), the proposed OF control with CI and DD measurements, with (· · · ·) and without (- - -) parameter error, and setpoints (····).

Figure 1 shows that the proposed OF controller with CI and DD measurements: (i) stabilizes the volume, temperature and monomer (related to the stability and the production rate level) in about 1 residence time; (ii) regulates the MW also in about 1.2 residence time, or in other words, the MW response is almost twice faster than the response of the PI-inventory without MW measurements (González and Alvarez, 2005), and 3.5 times faster than an open-loop response (with a settling time of 4 residence times); (iii) regulates the outputs with similar times that the ones of the exact model-based SF controller (5); and (iv) is not affected by presence of the parameter error, yielding a MW response without offset.

6. CONCLUSIONS

An output-feedback controller to continuous free-radical polymer reactor was presented, driven by continuous-instantaneous volume, temperature and flows measurements, and discrete-delayed molecular weight measurements. The measurement-driven controller consists of: (i) linear PI-type decentralized volume and cascade temperatures, (ii) a linear and decentralized cascade MW controller, and (ii) a material-balance monomer controller. The temperature controller requires two approximate static parameters, the monomer controller requires the heat capacity function, and both controllers are based on a continuous estimator. The MW controller is based on a discrete estimator, and requires one static parameter and initiation constants (pre-exponential factor and activation energy), which are fewer modeling requirements than the ones of the case without MW measurements. The proposed control technique has a systematic construction and simple tuning guidelines, and the solution polymerization of MMA in an open-loop unstable industrial size reactor was considered as application example with numerical simulations, yielding: (i) output responses with convergence times similar to the ones of an exact model-based state-feedback cascade control, (ii) a MW response that is almost twice faster than the response of a PI-inventory controller without MW measurements, and (iii) a MW response without offset, showing that the controller is not affected by parameter errors.

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