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Iterative learning dual-mode control of exothermic batch reactors

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Abstract

Control strategies of the on–off type can be used to bring batch reactor temperature to the set point in minimum time. A practical controller implementing this control strategy in industry is the dual-mode controller. When well-tuned, this controller shows excellent control performances for various batch reactors. However, the dual-mode controller may be sensitive to process changes. For improved robustness, the dual-mode controller is modified and equipped with an iterative learning technique. This iterative learning dual-mode controller requires minimal information from the previous batch runs and can be incorporated in the existing dual-mode controller with minimal effort.

Keywords: Dual-mode control; Iterative learning control; Batch reactor; Temperature control

1. Introduction

In an exothermic batch reactor, temperature overshoot is usually avoided because it can cause runaway due to the large amount of heat released at elevated reactor temperatures. On the other hand, reactor temperature should be increased as quickly as possible to the operating set point. Control actions to achieve this objective can be obtained by solving the time-optimal control problem (Cott and Macchietto, 1989). The resulting control actions are usually on–off controls, although sometimes a singular arc is optimal (Kirk, 1970). The minimum time control strategy can be implemented by a so-called dual-mode (DM) controller (Shinskey, 1996). Maximum heating is applied until the reactor temperature reaches within a specified number of degrees of the set point, and then maximum cooling is followed to bring the error to zero. When the reactor temperature has reached its desired set point, a standard PID controller is switched on and used to maintain the reactor temperature. Although the DM controller with two changes in input will not emulate the time-optimal control strategy perfectly, a well-tuned DM controller provides excellent system performance approximating the time-optimal control strategy. However, because the time-optimal control and its approximate DM control are model based, they are difficult to implement on new systems having robustness concerns.

For control strategies with improved robustness, several authors (Aziz, Hussain, & Mujtaba, 2000; Cott & Macchietto, 1989; Juba & Hamer, 1986; Jutan & Uppal, 1984) have proposed control systems that estimate the amount of heat being released in the reactor and use it to counterbalance the effect of the heat released. Although the estimation of heat release has some error and time delay, it compensates for the major nonlinearity in the reactor dynamics and control system. To design the estimator, the reactor temperature and its time derivative, the jacket temperature and some process parameters are required.

Iterative learning control (Lee, Bang, Yi, Son, & Yoon, 1996; Lee & Lee, 2007) has been used to control the temperature in an exothermic batch reactor. It uses previous batch information to eliminate the tracking error and reject repetitive disturbances. Because the iterative learning control cannot handle random disturbances, feedback control is also incorporated to reduce the effects of such random disturbances and to accelerate the convergence of the iteration. Because initial control actions for heating the batch reactor

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Nomenclature

C_p	mass heat capacity of reactor contents (kcal/kmol °C)
C_{pi}	molar heat capacity of component i (kcal/kmol °C)
ΔH_i	heat of reaction i (kcal/kmol)
E_m	approach temperature difference for dual-mode controller (%)
K_c	dual-mode controller PID gain
k_{i1}, k_{i2}	rate constants 1 and 2 for reaction i
M_i	number of moles of component i
MW_i	molecular weight of component i (kg/kmol)
PL	preload temperature of dual-mode controller
ρ	density of reactor contents (kg/m^3)
R_i	reaction rate of reaction i (kmol/min)
T	temperature (°C)
t	time (min)
τ_D	dual-mode controller PID derivative time (min)
TD_1	length of time full cooling is applied in dual-mode controller (min)
TD_2	length of time preload is applied in dual-mode controller (min)
τ_I	dual-mode controller PID integral time (min)
UA	(heat transfer coefficient of reactor) (heat transfer area) (kcal/min °C)
V	volume (m^3)

Subscripts

1	reaction 1 ($A+B \geqslant C$)
2	reaction 2 ($A+C \geqslant D$)
A, B, C, D	components A, B, C, and D
J	jacket
R	reactor
sp	set point

Superscripts

$[k]$	batch count

are usually on–off, iterative learning controls based on constrained optimization are required.

In order to obtain a simpler and more easily understandable method, the conventional DM controller is modified and incorporated with the iterative learning technique. Specifically, the cooling period is adjusted to prevent thermal runaway or overcooling, and switching criteria are adjusted iteratively from the previous batch runs (run-to-run control) to maintain the system performances. Minimal information from previous batch runs is required. Simulations show that the improved DM controller can avoid thermal runaway for various process changes and the iterative learning technique achieves satisfactory control performances.

2. Exothermic batch reactor

The target process is described first for the notational convenience. Temperature control of the exothermic batch reactor shown in Fig. 1 is considered. Here, a proportional control system for the jacket temperature is already designed and closed. It uses a split range control (Seborg, Edgar, & Mellichamp, 2003),which switches the cooling water and steam according to the range of manipulated variable. The reactor temperature, T_r, is controlled by manipulating the set point of the jacket temperature, T_{jsp}. This is a kind of cascade control and the purpose of this work is to design the outer loop of this system. The reaction chemistry is the same as that in Cott and Macchietto (1989) and Aziz et al. (2000).

Reaction 1:

$A+B \rightarrow C$.

Reaction 2:

$A+C \rightarrow D$,

where A and B are the raw materials, C the desired product, and D the waste product.

The model equations for this batch reactor can be written as

$$\frac{dM_A}{dt} = -R_1 - R_2,$$

$$\frac{dM_B}{dt} = -R_1,$$

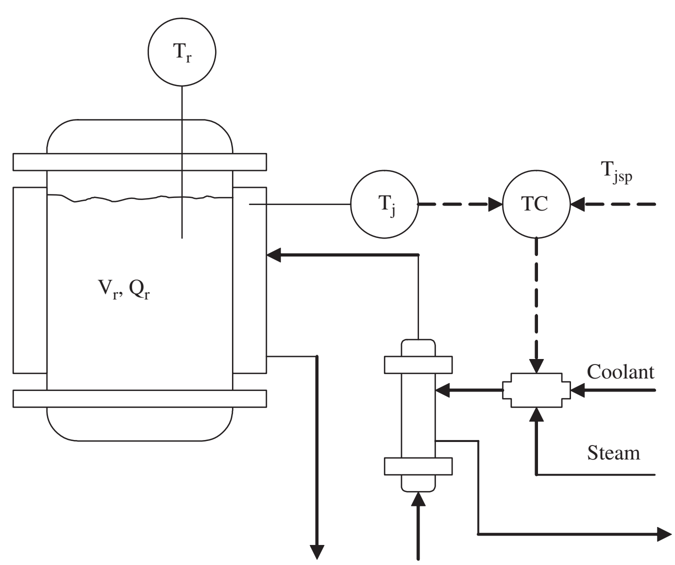

Fig. 1. An exothermic batch reactor with a jacket temperature control system (TC: temperature controller).