Available online at www.sciencedirect.com
ScienceDirect
IFAC Papers Online
CONFERENCE PAPER ARCHIVE
IFAC-PapersOnLine 48-30 (2015) 209–214

Model-based Control of an Energy-integrated Batch Reactor - Feed Effluent Heat Exchanger System in a Campaign Mode ⋆

Sujit S. Jogwar *

* *Department of Chemical Engineering, Institute of Chemical Technology, Mumbai, 400019, India (e-mail: ss.jogwar@ictmumbai.edu.in).*

Abstract: In this paper, a novel model-based cascade control strategy has been developed for an energy-integrated batch reactor-feed effluent heat exchanger system. The presence of two time scales facilitates implementation of such a cascade strategy. An input-output model is developed for the slow dynamics of the system and is used for the design of a model-based controller to achieve desired product purity. The effectiveness of the proposed control strategy for disturbance rejection and operating point transitions is demonstrated with the help of simulation studies. The proposed strategy promises direct saving of energy, material and time.

Keywords: Batch Process Modeling and Control, Energy Integration, Cascade Control

1. MOTIVATION

Energy integration is one of the frequently used tools by modern process industries to gain a significant competitive advantage. Energy integration aims at coupling the heating and cooling energy requirements in a system and reduces the utilization of energy from external sources. Energy integration thus improves the overall energy efficiency of a process. Such integration, however, increases coupling between different sections of the system, motivating the need for an intelligent control system to account for such interactions.

While the design, operation and control of energy-integrated processes with continuous operation have gained significant attention in the last couple of decades, extension of such efforts to batch systems has received less attention. Time dependent integration opportunities and a small quantum of energy savings have been the prime reasons behind such reduced interest in energy integrated batch systems. However, fluctuating energy prices and increased competition have increased efforts in the design of energy-integrated batch systems (Kemp and Deakin, 1989; Zhao et al., 1998; Majozi, 2006; Halim and Srinivasan, 2008). Still, operation and control of such systems has received little consideration.

Motivated by this, developing effective control strategies to enable disturbance rejection and smooth operating point transitions for such integrated systems has been the goal of current work. In previous work (Jogwar and Daoutidis, 2015a), it has been shown that tightly integrated batch process systems exhibit dynamics over two time scales. The individual batches evolve at the fast time scale whereas the interaction (introduced via energy integration) between batches leads to slow network-level dynamics. Furthermore, the fast dynamics is continuous (intra-batch dynamics) and the slow dynamics is discrete (inter-batch dynamics).

Use of process models to address control and optimization for general batch processes has been pursued in the context of advanced control (geometric control, model predictive control, etc.). For example, Cott and Macchietto (1989) developed an extension of the generic model control framework for temperature control of an exothermic batch reactor. Soroush and Kravaris (1993) developed a unified framework for design, modeling, dynamic optimization and control using globally linearizing control methodology. Nagy and Braatz (2003) developed a shrinking horizon nonlinear model predictive control for batch processes. Palanki et al. (1993) developed state-feedback laws to address end of the batch optimization objectives.

In a different vein, control of repetitive batches (campaign mode) has also been pursued, particularly using data-driven models. For example, Flores-Cerrillo and MacGregor (2003) have developed a partial least square-based approach to address batch-to-batch control objectives. Lee and Lee (2007) have developed an iterative learning control strategy to improve tracking performance of batch processes. Srinivasan et al. (2003) have developed a framework of tracking the necessary conditions for optimality and thereby achieving optimal operation. Jogwar and Daoutidis (2015b) have developed a data-based model to capture the batch-to-batch evolution of an energy-integrated batch reactor-feed effluent heat exchanger (BR-FEHE) system and used it to manipulate the production schedule in order to optimize overall energy consumption in the presence of variations in the supply and cost of energy.

⋆ Partial financial support for this work by the Government of India Department of Science and Technology (DST) INSPIRE & SERB-SB/S3/CE/090/2013 grant is gratefully acknowledged.

10.1016/j.ifacol.2015.12.379

The focus of the current work is to develop a control strategy for the control of the desired product purity while exploiting the batch-to-batch slow dynamics arising due to energy integration. To this end, a cascade control strategy is proposed wherein,

- a fast controller maintains the reactor inlet temperature within a batch, and
- a slow controller maintains the desired product purity in a product tank by manipulating the set point of the reactor inlet temperature controller (for the next batch).

The rest of the paper is organized as follows. Section 2 describes the BR-FEHE system and defines the problem addressed in this paper. The development of an input-output model for the slow dynamics and the subsequent design of the model-based purity controller is included in section 3. In section 4, the effectiveness of the proposed strategy is demonstrated via simulation studies.

2. ENERGY-INTEGRATED BR-FEHE SYSTEM

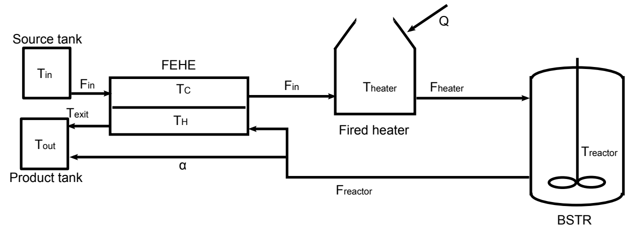

Fig. 1. BR-FEHE system with direct energy integration

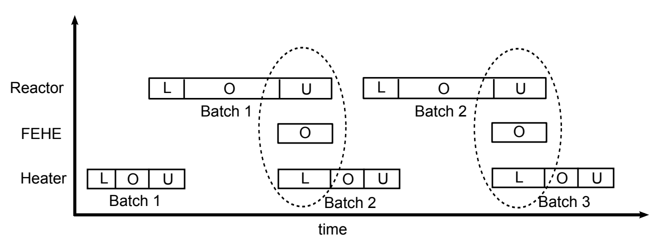

Fig. 2. Gantt chart representing schedule for the BR-FEHE system (L: loading, O: operating, U: unloading). The energy integration is shown by the dotted circle

Figure 1 shows a BR-FEHE system where a set of two mildly exothermic consecutive reactions (A $\rightarrow$ B $\rightarrow$ C) are carried out in the batch reactor. The intermediate component B is the product of interest. The reactions are carried out at an elevated temperature (880-890 K) and the feed is available at the room temperature (300 K). Energy saving can be achieved by using the hot reactor effluent to preheat the cold feed. As the feed preheating needs to be done before the reactor effluent is available, the cold feed in the i^{th} batch is preheated in the FEHE using the effluent from the $(i-1)^{th}$ batch as depicted in the Gantt chart shown in Figure 2. The fired heater is used to bring the FEHE outlet temperature to the desired reactor inlet temperature. The cooled reactor effluent from the reactor is stored in the product tank. It is considered that the batch production campaign is run for a set of 50 consecutive batches and the resulting material in the product tank is considered as the final product. The detailed dynamic model (based on unsteady state material and energy balances) for this system is presented in Jogwar and Daoutidis (2015a) and is not reproduced here.

This system operates at high energy efficiency. In the absence of energy integration, the system requires 10.68 MW energy. Energy integration allows recycling of 96% of this energy internally, thereby dropping the external energy consumption in the integrated system to a mere 0.39 MW. For such a tightly integrated system, it has been shown that the various temperatures and concentrations exhibit two-time scale dynamics - a fast scale capturing the dynamics within a particular batch and a slow time scale capturing the batch-over-batch evolution, typically triggered via a disturbance. The objective of the control system is to maintain/achieve the desired concentration of component B in the product tank in the presence of unmeasured disturbances in the feed conditions as well as major process upsets (for example, reduction in heater power) in a batch. Typically, in the event of such disturbances, that particular batch is spoiled and discarded, resulting in material as well as energy losses and schedule delays. The objective of the current work is to consider this spoiled batch as a disturbance and compensate for its effect by updating the subsequent batches. To this end, the slow model capturing the batch-to-batch evolution of key process variables is utilized to predict and replan the batches following the disturbance.

In order to achieve these control objectives, a cascade control strategy is proposed wherein

(1) the reactor inlet temperature (or heater exit temperature) in a particular batch is regulated at its set point using the duty of the fired heater as a manipulated input, and
(2) the concentration of the component B at the end of a batch (or campaign) in the product tank is controlled at its desired value by manipulating the set point of the heater temperature controller.

Such a cascade control strategy is possible as the first control objective is addressed in the fast time scale (within batch objective), whereas the second control objective is addressed in the slow time scale. The development of the model and the corresponding model-based controllers for each time scale is presented in the next section.

3. MODEL DEVELOPMENT AND CONTROLLER DESIGN

The dynamic equation governing the evolution of the heater temperature during heating phase is given by the following equation.

$$\frac{dT_{heater}}{dt} = \frac{Q_{heater}}{V_{heater}\rho C_p} \tag{1}$$

It is assumed that the heater is 100% efficient and there are no losses. If the initial temperature in the heater is $T_{heater,0}$ and the desired heater temperature is $T_{heater,set}$, the required heater duty (constant heating rate) can be given as follows.