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Modeling, simulation and control of a scheibel liquid–liquid contactor Part 2. Model-based control synthesis and design

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Abstract

This study describes an application of model-based control techniques to a liquid–liquid extraction process. The control design is based on a reduced order model of the process obtained by system identification. A multi-loop decentralized control system, in the framework of internal model control (IMC), is initially selected to control the 2 × 2 control loops of the extraction column. The interaction of loops is then investigated to explore the feasibility of such multi-loop control structure. A centralized multivariable control system is synthesized with a model predictive control (MPC) technique. The simulation results demonstrate good servo and regulatory characteristics for both control system designs. However, the MPC control of extraction proved to be superior to the IMC one in terms of speed of response, stability, robustness, and loops interaction. MPC has also shown ability to handle control operation under input variables constraints, which has significant practical importance.

Keywords: Scheibel; Extraction dynamics; Liquid–liquid; Control; SISO; MIMO; imc; Model-based; MPC

1. Introduction

The objectives of controlling the extraction process include maintaining high product quality, avoiding or minimizing losses, maximizing throughput, minimizing operational costs, and ensuring safe and environment friendly operation depending on the processes application under consideration. An efficient control system design must ensure acceptable set point tracking and load rejection characteristics in terms of response time, stability and sensitivity to model mismatch. Controlling such a non-linear and involved process entails a great deal of computational effort.

Advanced non-linear control strategies [1–3] can be used to handle such systems. However, due to the computational load of these approaches, they become unattractive for such complex systems. The availability of reduced order models for the extraction process calls attention to the possible application of more advanced control schemes to solve the control problem. Real-time implementation of model-based control schemes using reduced order models has proved to be successful for continuous liquid–liquid extraction columns [4].

The underlying concept that governs the operation of model-based control schemes is their dependency on a process dynamic model. Examples of such schemes are internal model control (IMC) [5,6] and model predictive control (MPC) techniques [7], such as dynamic matrix control (DMC) [8] and model algorithmic control (MAC) [9]. The accuracy of the process model used dictates the efficiency and reliability. Consequently, accurate model identification becomes a crucial prerequisite for the design of such control schemes.

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Despite the practical significance of extraction processes, the literature shows very little control research effort especially in the multivariable treatment of the process. McDonald and Wilkinson [10] studied the control of a multiple mixer column. Three control schemes were proposed; conventional feedback, feed-forward and their combinations. Variations in feed flowrate resulted in an improper functioning of the feed-forward controller. They recommended the use of dynamic compensation to adjust the development of erroneous intermediate concentration profiles during the start-up using a feed-forward control scheme. Al Khani et al. [11] applied a model reference adaptive control system to a sieve plate pulsed extraction column. Their control law was based on a low order discrete model with time-varying parameter. The applied algorithm produced reasonable overall behavior, but was not able to handle the non-linearity of the process caused by the effect of operational parameters and the effect of start-up on the dynamics of the process. Najim and Lann [12] used a multilevel system of automata-based decentralized control algorithm operating in a random environment to adapt a learning control algorithm for the same column. This approach was based on artificial intelligence. Their study suffered from the lack of investigating the control system design and it was applied only on a single-input–single-output (SISO) system, where outlet continuous phase conductivity was controlled by pulse frequency. Tsouris and Tavlarides [13] used a first order-reduced model of the process to control the dispersed phase volume fraction. The Dahlin controller algorithm was used for this purpose. This study was concerned mainly with the hydrodynamic control of the contactor and no emphasis was given to the mass transfer control, which is of great importance to the process. Wichterlova and Rod [14] studied the control of a 6 stage box-type mixer-settler cascade. The control system design was selected based on practical experience, and was not based on a systematic approach. The final design was not tested for stability and robustness under the whole range of operating conditions. Recently, Weinstein et al. [4] proposed a multi-loop model-based control system design to control an extractor, utilizing reduced order models derived from a continuous rigorous dynamic model. Their study lack experimental verification but was a good attempt in this direction.

From the above, one can realize that there is a great need to focus on the multivariable nature of the process and develop a practically simple, yet accurate, control algorithm for handling its dynamic behavior.

This study is an extension to previous modeling and system identification work, conducted on a Scheibel extraction column. The column has been modeled by the mixing stage with backmixing [15], which has been validated with the column data. Input–output response data have been generated from the rigorous model via system identification. The developed simple reduced-order linear models are used in this work in order to synthesize model-based control schemes for the extractor. The servo and regulatory performance of this control scheme are studied and compared to conventional control algorithms.

2. Control system design

2.1. Control synthesis problem

In view of the fact that the liquid–liquid extraction process is multivariable in nature, the solution of the control problem should take this into consideration. A first step in studying any dynamic system is the classification of variables involved in the operation of the process under consideration. The liquid–liquid extraction process involves many variables, which contribute to its operation, and this makes it a multi-input multi-output (MIMO) process. Following the classification step, the synthesis problem can be tackled. By this we mean the selection of the best manipulated-controlled variables pairs that can be used to control the plant. Many analytical methods are available for variables pairing such as relative gain array (RGA) [16], singular value decomposition (SVD) [17] and Jacobi Eigenvalue criterion (JEC) [18]. Furthermore, the selected pairings should have minimum interaction among variables. The frequency-dependent relative gain array analysis (DRGA) [19] ensures that the whole spectrum of operation is covered in the analysis.

The extraction process transfer function is considered as a 2 × 2 system with the rotor speed (N) and the solvent feed flowrate (S_f) as manipulated variables (MVs), and the outlet raffinate concentration (x_out) and the extract outlet concentration (y_out) as controlled variables (CVs). The process transfer matrix (G) can be represented as in Eq. (1) as:

$$\begin{bmatrix} x_\mathrm{out} \\ y_\mathrm{out} \end{bmatrix} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix} \begin{bmatrix} N \\ S_\mathrm{f} \end{bmatrix} \tag{1}$$

where g_{ij} represents an open loop transfer function relating controlled variable (i) to the manipulated variable (j).

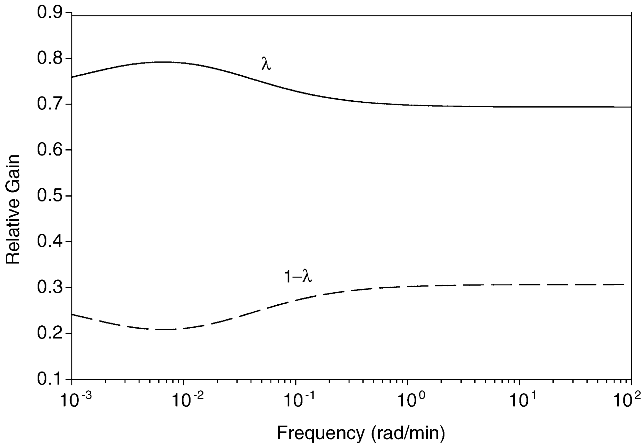

Fig. 1. The variation of the RGA elements magnitude with frequency.