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Systematic control structure evaluation of two-stage-riser catalytic pyrolysis processes

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HIGHLIGHTS

- Control structure candidates of the TSRFCP process are generated based on heuristic knowledge.
- Extended bifurcation diagrams are utilized to screen the generated candidates.
- Closed-loop multiplicity is used to compare control actions under disturbances/uncertainties.

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ABSTRACT

Control structure selection plays an irreplaceable role in achieving an effective control system. Through the application of steady-state multiplicities and classic control theories such as zero dynamics and relative gain arrays (RGAs), the primary goal of this article is to select the best control structure from the selected candidates based on heuristic reasoning for a demonstration two-stage-riser catalytic pyrolysis process which can maximize propylene yield without any significant losses in gasoline/diesel yields. Extended bifurcation diagrams and RGAs are adopted to preliminarily evaluate candidates from open-loop perspectives. Closed-loop steady-state multiplicity, which is employed to compare control actions associated with each control structure, can provide a solid basis for the synthesis of control loops. Dynamic simulations for tackling disturbances and tracking set points are finally carried out to evaluate the relevant maximum deviations and settling times under various scenarios. It is illustrated that output temperatures from two risers and the regenerator controlled by two recycled catalyst flow rates and the cooling water flow rate, respectively, which have the best controllability characteristic and most superior dynamic behavior, are the most suitable control structure for further control system design of the studied process.

1. Introduction

New fluidized catalytic techniques such as Two-Stage-Riser Fluidized Catalytic Pyrolysis (TSRFCP) for maximizing propylene yield are recognized as the efficient routes to handle the expanded propylene supply/demand gap and to moderate the increased propylene price (Li et al., 2007). Due to strong interactions between exothermic reactions of catalyst regeneration in the regenerator and endothermic pyrolysis reactions in two risers, the TSRFCP process exhibits complex nonlinear behavior which may lead to difficulties in operation. Furthermore, product quality requirements, equipment capacity constraints, along with environmental/safety considerations drive the TSRFCP process to operate close to its operational boundaries such as minimization of dry gas yield, or maximization of propylene yield without reducing gasoline/diesel yields. A wide spectrum of disturbances may cause the TSRFCP operation to deviate from the designed operation point, and hence performance deteriorates. Apparently, high-efficient control mechanism for the TSRFCP process is greatly needed. To some extent, the selection of the proper primary control structure is far more important than the detailed algorithm used in designing the actual controllers for a given structure (Arbel et al., 1996). Based on the validated mathematical model, this paper focuses on the evaluation of control structures which are selected based on heuristic reasoning for the TSRFCP process.

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The selection of control structure traditionally contains manipulated variable (input) selection, measurement (output) selection, and control configuration (input–output partitioning and pairing) selection (Skogestad and Postlethawaite, 1996; Skogestad, 2004). There are usually a certain number of controlled/manipulated variable candidates for a chemical process. These candidates can be divided into subsets to generate several alternative schemes, so that performance of these candidates can be compared to generate the best control structure (Cao and Rossiter, 1997). Since control structure selection is a combinatorial problem, the number of possible control schemes grows very rapidly with respect to the number of available inputs and outputs. As nonlinear features of a chemical process to be controlled are dominant in the selection of the best control structure, the control structure selection issue can be simplified dramatically if the operating policy is determined in advance based on steady-state analysis (Ward et al., 2010). In other words, designing a control strategy for a nonlinear process can benefit a lot from thorough elucidations of nonlinear features. Existing contributions have demonstrated that selecting the best sets of input and output variables along with the corresponding controllability performance are traditionally governed by classical control theories such as open-loop gains, relative gain arrays (RGAs), right half plane (RHP) zeros, Non-Minimum Phase (NMP) behavior, and singular value analysis (Stephanopoulos and Ng, 2000; Yuan et al., 2011a). An introduction to the differences and similarities between RHP zeros and phase behavior should be given.

Whether the control for a chemical process can be easily realized or not can be determined by the inverse characteristic of the studied process (Morari, 1983). For a linear system, zeros are the roots of numerator polynomial and are the poles of the inverse of its transfer function. A linear system with RHP zeros may exhibit inverse response which imposes limitations on control performance and poses difficulties for controller design. Apparently, the inverse characteristic of a nonlinear process may change with changes in operating conditions. On the other hand, it is sometimes difficult or impractical to obtain the transfer function for a highly nonlinear system over a wide range of operation. Zero dynamics, which is analogous to the notion of zeros of a linear system, is described here (Isidori, 1989). Generally speaking, zero dynamics for a nonlinear system can be defined as the internal dynamics when the system output is kept constant (Isidori, 1989; Slotine and Li, 1991). A nonlinear system with unstable zero dynamics demonstrates NMP behavior and expresses inverse responses. Single-input-single-output nonlinear systems with input multiplicity have stability changes in their inverse, and thus place limitations on the structure of the feedback controller (Koppel, 1982; Sistu and Bequette, 1995). For multi-input-multi-output nonlinear systems with input multiplicity, there must exist unstable zero dynamics (NMP behavior) on one side of the steady-state operating curve (Russo and Bequette, 1995). Relationships between the (N) MP behavior and operating/design conditions for both single units (Yuan et al., 2011b) and process networks (Yuan et al., 2012) have been widely investigated.

The increased academic and industrial interests in developing effective control systems have led to considerable applications of the aforementioned controllability measures for control structure evaluation. A large number of approaches ranging from heuristic/engineering driven strategies to optimization based frameworks have been proposed for single units and plant-wide chemical processes. Lau et al. (1985) proposed a singular value decomposition (SVD) based approach to synthesize the regulatory control structure for a distillation column. Based on this SVD approach, quantitative measures of interaction and sensitivity for the nodes, as well as for the entire process can be established. Steady-state multiplicity based rangeability in conjunction with the conventional sensitivity analysis has been used to evaluate control structures for a reactive distillation column (Kumar and Kaistha, 2008). Similarly, Yuan et al. (2011c) have taken a polymerization reactor as an example to reveal connections between the selection of manipulated variables and phase behavior/open-loop stability characteristic. Steady-state multiplicity clearly plays an important role in the control structure selection. Systematic approaches based on heuristics and dynamic simulations have been intensively used for synthesizing control structures for large-scale chemical processes (Luyben et al., 1997; Murthy et al., 2005; Araujo and Skogestad, 2008; Vangsgaard et al., 2014). In addition, optimization based frameworks have also been widely investigated. General topics involved in this category include performance indicators such as condition number, minimum square deviation, and robustness indicators based optimization frameworks (Seferlis and Grievink, 2001; Zumoffen, 2013), steady-state optimizing approaches (Morari et al., 1980; Arkun et al., 1980; Baldea et al., 2008; Jagtap et al., 2013), back-off based optimization (Heath et al., 2000; Psaltis et al., 2013), inverse model based approach (Sharifzadeh and Thornhill, 2012, 2013), robust control theory based optimization (Ricardez-Sandoval, 2012; Sanchez-Sanchez and Ricardez-Sandoval, 2013; Gutierrez et al., 2014), mixed integer dynamic optimization (MIDO) based framework (Mohideen et al., 1996; Bansal et al., 2002; Sakizlis et al., 2004), integrated heuristic and optimization (Assali and McAvoy, 2010; Tripathi et al., 2013). However, the different approaches have their individual drawbacks. For example, with regard to the performance indicators based optimization approaches, closed-loop controllability/robustness properties, which are calculated based on steady-state models or linear nominal dynamic models, limit their further applicability to those systems that exhibit highly nonlinear dynamic behavior. The computational complexity caused by the resulted complex large-scale mixed integer nonlinear programming problems is a key obstacle for MIDO based approaches. For robust control theory based approaches, *a priori* knowledge of the dynamics of parametric uncertainty is needed. A comprehensive overview of these optimization based approaches can be found elsewhere (Yuan et al., 2011a).

Similar to other chemical processes, nonlinear behavior and strong interactions between individual control loops constitute major challenges in the design and implementation of control systems for fluidized catalytic cracking (FCC) processes (Lee and Weekman, 1976). Existing research work has demonstrated that different paired manipulated/controlled variables depict distinct nonlinear behavior (Alhumaizi and Elnashaie, 1997). Extensive literature has been concentrated on the control structure selection for FCC processes. Based on RHP zeros, RGAs, partial RGAs, and closed-loop disturbance gains, Hovd and Skogestad (1993) have evaluated the regulatory control structure for the FCC process under partial and complete combustion modes. Their results have illustrated that, for the partial combustion model, Hick control structure is the most suitable one. Arbel et al. (1996) have presented a systematic methodology, which includes modelability, dominance, nonlinearities, time scale of response, and sufficiency, to evaluate control structure candidates for the FCC unit. Through the input multiplicity analysis, controlling the riser outlet temperature and the outlet oxygen composition of the flue gas by the circulated catalyst flow rate and the combustion air flow rate has been demonstrated to be the best control structure for a UOP FCC unit with complete combustion mode (Fernandes et al., 2007), and this conclusion agrees with those previous contributions (Arbel et al., 1996; Hovd and Skogestad, 1993). RGAs coupled with closed-loop dynamic simulations have been employed for the control structure selection for a realistic high-efficiency FCC unit (Fernandes et al., 2008). This work reaches the conclusion that the best control structure includes the riser reactor temperature, the tripper bed level, the regenerator pressure and the oxygen concentration in the flue gas as controlled variables together with the regenerated catalyst slide valve, the spent catalyst slide valve, the flue gas valve, and the combustion air flow rate as manipulated variables. Maya-Yescas et al. (1998, 2003) have proposed a zero dynamics based framework to investigate the phase behavior under different operating policies. Such an approach can help us to clarify the roots of the complex phenomena that arise in the design and control of the FCC process.

Based on the detailed nonlinear model of the TSRFCP process (Liu, 2008; Wang et al., 2014) and according to the selected control structures based on heuristic reasoning, this paper focuses on the evaluation of the selected candidates for the TSRFCP process through applying classic