Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Dynamic simulation and control of an integrated gasifier/reformer system. Part II: Discrete and model predictive control

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ARTICLE INFO

Article history:
Received 13 November 2014
Accepted 3 May 2015
Available online 12 May 2015

Keywords:
Steam methane reforming
Gasification
Dynamic simulation
Polygeneration
Model predictive control

ABSTRACT

Part I of this series presented an analysis of a multi-loop proportional-integral (PI) control system for an integrated coal gasifier/steam methane reformer system, operating in both counter-current and co-current configurations, for syngas production in a flexible polygeneration plant. In this work, a discrete-PI control system and an offset-free linear model predictive controller (MPC) are presented for the co-current configuration to address process interactions and sampling delay. The MPC model was identified from 'data' derived from simulations of the rigorous plant model, with a Luenberger observer augmented to the MPC, to estimate and eliminate plant-model mismatch. MPC offered superior set point tracking relative to discrete-PI control, especially in cases where discrete-PI destabilized the system. The offset-free MPC was developed to solve in less than a second to facilitate online deployment.

1. Introduction

In Part I of this series, rigorous dynamic models of a novel integrated coal gasifier/steam methane reformer system (RSC/SMR) were used to develop a control structure and to assess the operability of the system under expected industrial conditions (Seepersad et al., 2015). The concept for the RSC/SMR was first introduced by Adams and Barton (2011), who illustrated that for a polygeneration plant, improvements in efficiency and profitability can be realized by performing the steam methane reforming (SMR) reactions within the tubes of the gasifier's radiant syngas cooler (RSC). This configuration capitalizes on available exergy by using the sensible heat of the high-temperature coal-derived syngas to drive the strongly endothermic reaction, producing H_2-rich synthesis gas (syngas) in place of high pressure steam. However, that work only discussed the concept from a systems perspective to determine if it was worth pursuing. The RSC/SMR unit itself was never studied, modeled, or designed in any degree of detail. Later, a rigorous dynamic model for the system was developed by Ghouse et al. (2015), to design and study operational feasibility of the proposed system. Open loop analysis of the integrated system showed that a number of potential issues could arise during its operation and that they needed to be considered when constructing a control system (Ghouse and Adams, 2014).

Next, a proportional-integral (PI) control system was proposed in Part I of this series (Seepersad et al., 2015) for each of the two design variants of the RSC/SMR: counter-current configuration and co-current configuration. Despite an increasing adoption and interest in advanced control methods, PI control remains the most popular and trusted form of control due to its simplicity, maturity and rapid implementation. As such, PI control was used in Part I to encourage rapid acceptance by industry. Several desirable characteristics for the co-current RSC/SMR system were demonstrated: PI control achieved acceptable responses for set point changes, reliable disturbance rejection, and an ability to maintain tube

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http://dx.doi.org/10.1016/j.cherd.2015.05.007
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Nomenclature

Abbreviations

CV	Controlled Variable
IAE	Integral Absolute Error
IMC	Internal Model Control
MPC	Model Predictive Control
MV	Manipulated Variable
PI	Proportional-Integral
RSC	Radiant Syngas Cooler
S/C	Steam-to-Carbon ratio
SMR	Steam Methane Reformer
ZOH	Zero-Order-Hold

Subscripts

i	discrete sample index
L	linear
NL	non-linear

Superscripts

in	inlet

Symbols

E	error
F_{SMR}	total molar feed flow to SMR tube
k	sampling instant
K_C	controller gain
$\mathbf{L}$	Luenberger gain matrix
M_S	shell gas mass flow rate
N	control horizon
P	prediction horizon
$R_{S/C}$	steam-to-Carbon ratio
S	discrete error summation
SP	set point
T_S	shell gas temperature
T_{gas}	SMR exit gas temperature
y_{CH_4}	CH_4 slip

Greek letters

Δt	sample time
θ_d	dead time
Θ	fictitious disturbance state
τ_p	process time constant
τ_i	integral time constant

wall temperatures well below their maximum limits. However, controller interactions were quite significant, and the study utilized continuous controllers, which is a somewhat idealized case and does not take into account hardware limitations of measurement devices.

In more realistic scenarios, the use of digital PI control (instead of continuous PI control) can introduce stability problems into the PI loops. In Part II (this work), the effects of using digital PI control and the impact of differences in sampling times are examined. In addition, a Model Predictive Controller (MPC) is developed which yields better control performance compared to the multi-loop digital PI design. Since the results of Part 1 of this series showed that co-current design is significantly more difficult to control than the counter-current design (slower settling times, more oscillatory behavior), only the co-current design is studied in this work as a "worst case". As such, the methodology employed herein can be extended to alternative designs. The reader is referred to Part I of this series for a description of the configuration of the RSC/SMR unit, the PI control system configuration, the model and the simulation cases used.

2. Implementation of digital PI control

2.1. *Digital PI model and implementation*

The control results presented in Part I of this series can be considered to be the best PI feedback response theoretically achievable due to the continuous signals received by the controllers. In reality, however, the hardware that is utilized to obtain process measurements must invariably take time to process the sample and transmit a measurement signal to the controller. With increasing sampling frequency (decreasing sampling time), the digital PI control performance tends toward continuous PI control. As was used in Part I of this series, the two controlled variables (CVs) defined for this system are: SMR tube exit gas temperature (T_{gas}) and SMR tube CH_4 slip (y_{CH_4}); the manipulated variables (MVs) are: total flow rate into the SMR tube (F_{SMR}) and steam-to-carbon ratio ($R_{S/C}$). Considering the CVs defined for this system, the CH_4 slip control is more likely to suffer from long sampling times.

The problem is two-fold: firstly, the dynamics of y_{CH_4} ($\tau_p \approx 10$ s) are significantly faster than the T_{gas} dynamics ($\tau_p \approx 200$ s), where τ_P represents the time taken for the CV to complete 63.2% of its step-response trajectory; secondly, CH_4 slip (y_{CH_4}) requires a composition analyzer to measure, which can suffer from long sample times relative to common temperature sensors (Marlin, 2000). As an example, one particular composition analyzer vendor offers a product specifically tailored to industrial NG and syngas applications (Precisive LLC, 2013). The Precisive analyzer feedback frequency can be user-adjusted between 1 s and 5 min, with longer sample times corresponding to higher measurement accuracy.

The digital PI controller model differs from the continuous PI controller form; the full position version was used in this work (Marlin, 2000):

$$V_k = \text{Bias} + K_C[E_k + \frac{\Delta t}{\tau_I} S_k] \tag{1}$$

$$S_k = \sum_{i=1}^{k} E_i = E_k + S_{k-1} \tag{2}$$

$$E_i = SP_i - CV_i, \tag{3}$$

where K_C and τ_I are the tuning parameters, E_i is the i^{th} sampled error, k is the current sample, Δt is sampling time, and S_k represents the summation of past and present errors (analogous to integrating the error in continuous time). As it is not possible to implement a discrete model explicitly within gPROMS (all equations are inherently continuous), the act of sampling and determining the next controller move takes place within a Task(Process Systems Enterprise, 2011). A Task is used in gPROMS to specify an operating procedure, which in this case (see Fig. 1 for description) is periodic and constitutes: (1) sampling the CV, (2) implementing a new control action (MV) and (3) maintaining that MV for the controller sample time.

This discrete sampling imposes a zero-order-hold (ZOH) on the process measurement. The continuous time signal of the process can be perfectly reconstructed from the discrete measurements, albeit with a phase lag of $\Delta t/2$ from the original