Fuel 234 (2018) 526–537

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Application of piece-wise linear system identification to solvent-based post-combustion carbon capture

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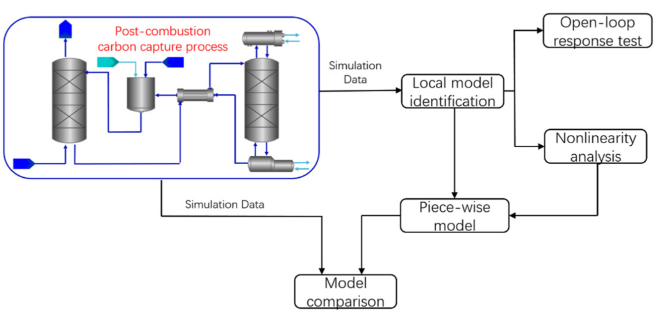
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Post-combustion carbon capture
Solvent-based carbon capture
System identification
Piece-wise model
Nonlinearity analysis

ABSTRACT

Solvent-based post-combustion carbon capture (PCC) is currently the most promising method to reduce CO_2 emission. To achieve a plant-wide controller for flexible operation, it is necessary to develop a data-driven model to understand the dynamic characteristics of PCC plant. This paper aims to: (i) carry out system identification to develop a data-driven model and (ii) provide insights into the nonlinear dynamics among the key variables from the PCC process in a wide operating range. These key variables include: CO_2 capture rate, reboiler temperature, condenser temperature and lean solvent temperature. Pilot-scale PCC process implemented in gCCS was used to generate simulation data for system identification and model comparison. Linear single-input-single-output (SISO) transfer function models were firstly developed at different capture rates. Open loop step tests on identified models were then introduced to report the dynamics of key variables in various operating conditions and to indicate the level of system nonlinearity graphically. The nonlinearity analysis was carried out to investigate the system nonlinearity distribution in a quantitative manner. Based on the nonlinearity analysis, a multi-input-multi-output (MIMO) piece-wise model was proposed to simulate the nonlinear characteristics of PCC plant. The piece-wise model shows a satisfactory agreement with gCCS simulation data. Results of this study successfully demonstrate the nonlinear behavior of the solvent-based PCC process, which can be applied in the design of flexible plant-wide controllers.

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https://doi.org/10.1016/j.fuel.2018.07.045
Received 8 May 2018; Received in revised form 8 July 2018; Accepted 9 July 2018

1. Introduction

1.1. Background

Global warming has increasingly drawn public attention. Extensive research has been performed to combat this trend. The Intergovernmental Panel on Climate Change (IPCC) stated that CO_2 contributed to about 50% of the increasing temperature in the earth surface among all the greenhouse gas [1]. Most of the CO_2 emissions originate from combustion of fossil fuels in large-scale power plants. For the near future, it is necessary to take measures to reduce CO_2 emission from these sources since fossil fuel is still attractive to meet future energy demands due to its rich availability, large energy density and low cost [2].

Among all the approaches, solvent-based PCC technology is viewed as the most mature option for existing power plants [3]. It offers advantages over other capture technologies because of high selectivity and pure CO_2 stream collection [3]. It can also be retrofitted as an end-of-pipe solution.

In the past decades, research efforts have been devoted to understanding the intricate nature of this carbon capture process. Solvent regeneration is energy intensive and it requires a lot of steam extracted from power plants. Given its high energy requirement, the solvent regeneration process will reduce the overall power plant efficiency significantly [4]. It is therefore important to minimize the energy demand and make more steam available for power generation [5]. However, it is still a matter of concern to find a trade-off to balance CO_2 removal rate and energy cost under the time-varying economic conditions. In this regard, there is a need to develop a flexible plant-wide control structure in order to achieve optimal performance in the presence of disturbance, load-changing and other scenarios. The nonlinear dynamic characteristics of PCC process need to be analyzed to provide information for the advanced controller's design.

1.2. Motivation

To study the dynamics of solvent-based PCC plant, several first-principle models have been developed (Lawal et al [5–7]). These models have been proven to be able to closely predict the real process. A number of carbon capture pilot plants are now available worldwide to provide steady-state or dynamic validation data (Dugas [8], Biliyok et al [9]). Nevertheless, it is clear that the simulation with first-principle models is computationally demanding. This makes controller design based on first-principle models difficult. Therefore, it is necessary to use a data-driven black-box identification method to serve as an alternative. On the other hand, most of the studies for PCC plant are focused on the linear models developed at a fixed operating point. Under varying operating conditions, the transient behavior of PCC plant will change and it would be difficult for linear models to simulate the nonlinear features. The linear model's failure to capture the nonlinear dynamics of the PCC plant will deteriorate the control performance. In order to develop a model predictive controller for wide-range capture rate change, Wu et al [10] proposed a simple nonlinear distribution analysis for solvent-based PCC plant. However, since multi-variable model is used in the analysis, the nonlinearity for a certain input-output loop cannot be revealed in detail. Motivated by these shortcomings, an investigation was carried out to further understand the operational features of a PCC plant over a wide range of operating conditions, and to identify possible control difficulties which may arise.

1.3. Aim of the study and main novel contributions

This study aims to identify a plant-wide black-box model based on piece-wise linear identification method. There are two major novelties in this paper:

- A fuzzy-based piece-wise model which can approximate the nonlinear dynamic features of a PCC process from 50% to 95% capture rate is achieved at a fixed power plant load. This model can be used for the plant-wide controller design.
- Detailed nonlinear characteristics of key variables in PCC process are researched quantitatively. These key variables include: CO_2 capture rate, reboiler temperature, condenser temperature and lean solvent temperature.

1.4. Outline

The paper is organized as follows: Section 2 presents the available literature review on modelling and identification of PCC process. Section 3 generates the simulation data of solvent-based PCC process in gCCS platform and uses these data to identify linear local SISO system models from 50% to 95% capture rate. In Section 4, a critical sensitivity analysis is performed by introducing step changes in the input variables. Nonlinearity degree analysis is carried out in Section 5. Section 6 presents the MIMO fuzzy-based piece-wise model. Conclusions are drawn in Section 7.

2. Literature review

Mass transfer and chemical reaction are two key factors to consider in modelling solvent-based PCC process. To describe the mass transfer process, two approaches are usually used in most studies: the equilibrium-based approach and the rate-based approach. In Lawal et al [6], a critical comparative evaluation showed that a rate-based model gives better agreement with experimental data.

To date, many studies on dynamic modelling have been implemented. In Kvanstal et al [11], a dynamic model of standalone absorber column in rate-based modelling approach was presented. This model was simulated in two load-varying cases, namely, start-up and load-reduction, to evaluate the operability of absorber. In Ziaii et al [12], a standalone stripper model was built in Aspen Customer modelling environment. Dynamic simulation was carried out to run the stripper flexibly during the period of high electricity demand and price.

However, the limitation of the aforementioned publications is that stand-alone model cannot represent the whole PCC process due to the intricate nature with regard to high nonlinearity and process interactions. Therefore, a dynamic model considered interacted units is significant to combine them together as a whole plant. Lawal et al [5] presented a dynamic model including absorber, stripper and recycle. Based on a comparative assessment, the whole process model gives more accurate results in predicting temperature profile than standalone columns. In their follow-up work [7], a scaled-up integrated model to industrial size of a 500 MW coal-fired subcritical power plant was made available. This work gave a preliminary technical evaluation of integrated PCC process and power plant. Due to lack of experimental data, dynamic validation is very rare. Biliyok et al [9] presented data at transient scenarios for dynamic model validation. In the same paper, dynamic process analysis proved that mass transfer is the major factor which limits CO_2 absorption.

First-principle model provides the advantage to realize accurate simulation, as well as understanding the underlying dynamics of the process. Nevertheless, as stated previously, first-principle model is computational intensive and it is hard to realize. Thus, carrying out black-box identification has emerged as an attractive alternative to first-principle dynamic modelling.

Arce et al [13] used Matlab™ identification toolbox (Ljung [14]) to obtain a linear model for solvent regeneration process. This model was composed of a first-order linear discrete transfer function with a sampling time of 200 ms. However, a first-order model cannot mimic the dynamic features compared with a higher order model. For capturing nonlinear characteristics, Manaf et al [15] employed a multivariable nonlinear autoregressive with exogenous input (NARX) model. To