Fuel 220 (2018) 931–941

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Flexible operation of post-combustion solvent-based carbon capture for coal-fired power plants using multi-model predictive control: A simulation study

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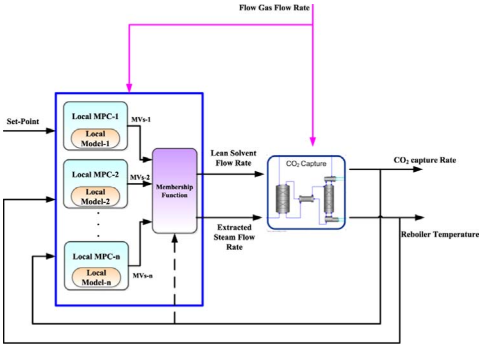
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Post combustion CO_2capture
Power plant
Flexible operation
Multi-model predictive control
Nonlinearity analysis
System identification

ABSTRACT

Solvent-based post-combustion CO_2 capture plant has to be operated in a flexible manner because of its high energy consumption and the frequent load variation of upstream power plants. Such a flexible operation brings out two objectives for the control system: i) the system should be able to change the CO_2 capture rate quickly and smoothly in a wide operating range; ii) the system should effectively remove the disturbances from power plant flue gas. To achieve these goals, this paper proposed a multi-model predictive control (MMPC) strategy for solvent-based post-combustion CO_2 capture plant. Firstly, local models of the CO_2 capture plant at different operating points are identified through subspace identification method. Nonlinearity analysis of the plant is then performed and according to the results, suitable local models are selected, on which the multi-model predictive controller is designed. To enhance the flue gas disturbance rejection property of the CO_2 capture plant and attain a better adaption to the power plant load variation, the flue gas flow rate is considered in the local model identification as an additional measured disturbance, thus the predictive controller can calculate the optimal control input even in the case of flue gas flow rate variation. Simulation results on an MEA-based CO_2 capture plant developed on gCCS show the effectiveness and advantages of the proposed MMPC controller over wide range capture rate variation and power plant flue gas variation.

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https://doi.org/10.1016/j.fuel.2018.02.061
Received 10 October 2017; Received in revised form 1 December 2017; Accepted 8 February 2018

1. Introduction

1.1. Background

With the increasing concern on global warming and its potential effect on climate, ecology and environment, CO_2 emission reduction has been regarded as a key step in the international community to alleviate these issues [1]. As the main power generation devices, coal-fired power plants (CFPPs) are the largest stationary emission source of CO_2 worldwide [2]. For this reason, while extensively promoting the renewable energy and making effort to improve the efficiency of conventional CFPPs, CO_2 capture from CFPPs has been recognized as the most effective and direct way to achieve a large-scale CO_2 emission reduction in the future 30 years [3].

Among various CO_2 capture technologies, solvent-based post-combustion CO_2 capture (PCC) using MEA solvent proves to be the most promising technology for CO_2 capture in power plants. Because it is well suited for treating flue gas at low CO_2 partial pressure of power plants, and can be easily installed for existing power plants retrofitting. In recent years, many PCC pilot plants have been developed and put into use [4,5].

The biggest issue for the operation of solvent-based PCC plant is the high heat consumption used for solvent regeneration. Such heat is generally provided by the steam extracted from the intermediate/low pressure turbine of the power plant, thus results in a significant power reduction of the CFPPs. To this end, many steady-state optimization studies such as equipment and solvent selection [6–9], system configuration [10–12], parameter settings [8,9] have been carried out, trying to improve the efficiency of the capture system. However, in the face of high energy consumption, more and more researchers realize that implementing flexible dynamic operation for CO_2 capture is of great importance to make the technology be widely used in power engineering practice [4,5,13–20]. During the electricity peak load, the capture system should be able to reduce its capture rate rapidly to avoid the high cost of energy. On the other hand, when there is tight restriction on CO_2 emissions or the carbon price is higher, the capture system could increase its capture rate quickly [21].

Another big issue, which has critical impact on the operation of the PCC system is from the integrated CFPPs. In the context of growing electric power demand, the magnitude of the cyclic variation of the grid load is increased, and the extensive use of renewable sources such as solar, wind and hydro power are severely influenced by the season and the weather condition, thus, CFPPs have to participate in the grid power regulation frequently and quickly in a wide range nowadays [22]. As a result, the flue gas flow rate of CFPPs will follow the load variation and change rapidly, which brings in strong disturbances to the capture plant [5]. Therefore, to achieve a wide range application, the PCC plants are forced to have a flexible adaption to the flue gas flow rate variation of upstream CFPPs.

1.2. Motivation

To overcome the aforementioned issues and to attain a flexible operation of PCC system, a well-designed control system is required to ensure the correct operation of the entire process, i.e. to follow the capture rate demand rapidly and smoothly in a wide range and to alleviate the influences of flue gas variation effectively.

Currently, most of the control studies of the PCC system are still stayed in the conventional PI/PID control stage [4,5,15,16,23–26] . Such a design has been proved for its value for regulation and disturbance rejection during normal operation around a given capture rate, however, it may not meet the design specifications for a high level flexible operation of PCC process, the reasons are: i) The CO_2 capture system is a multi-input multi-output (MIMO) system, while the PI/PID control systems are designed based on separate single-input, single-output (SISO) loops, thus the interactions among different variables and properties cannot be taken into account; ii) Due to the slow dynamics of chemical reaction and heat transfer, the PCC system has a typical large inertial behavior [5], while the control action of PI/PID controllers can only be made in the presence of deviation. This control manner may not meet the quick regulation need of the PCC system; iii) in general, the parameters of the PI/PID controllers are set at a given load condition. Therefore, when the flue gas flow rate of the upstream CFPP varies or the capture system changes its capture rate in a wide range, the operation performance of the PCC system is degraded because the dynamics at other operating points may become different.

Recently, model predictive control (MPC) [27], which uses a process model to predict the future response of the plant and calculate the optimal future control sequence has been employed in the PCC system control [13,14,17,18,28–34]. Since MPC is naturally suited for multivariable and large inertial system control, better performance has been shown compared with the conventional PI/PID controls. For most of the MPC designs in the CO_2 capture system, a linear model developed around a given operating point is used for the prediction [13,17,18,29,30,33,34], such a design may not be suited for a wide range capture rate variation because it is impossible for the linear model to approximate the global nonlinear dynamics. The resulting model mismatch will cause a severe control performance degradation or even unstable of the closed-loop system. To this end, a few scholars proposed to use nonlinear model predictive control (NMPC) [14,28,31,32]. However, it is hard to develop a satisfactory nonlinear model with high accuracy and good structure easy for advanced control design. Moreover the nonlinear optimization during the implementation of the NMPC is weak in robustness and time consuming.

On the other hand, the validations of the control systems in the case of upstream flue gas flow rate variation have been made in some studies. To our best knowledge, it still has not been studied regarding how to actively deal with its impact in the control design stage. Therefore, in spite of the effectiveness of MPCs in tracking the desired capture rate, it cannot remove or alleviate the flue gas disturbances rapidly.

These shortcomings motivate us to investigate the nonlinearity distribution of the solvent-based PCC system and to design a multi-model predictive control (MMPC) system using the combination of several local linear models and predictive controllers. The flue gas flow rate is considered as a measured disturbance in the developed model, so that correct model prediction can be made even in the presence of flue gas flow rate variation. The resulting MMPC system is expected to have a satisfactory capture rate tracking performance and flue gas disturbances rejection performance, and to provide a powerful method towards the flexible operation of the PCC system.

1.3. Literature review

The earliest studies of solvent-based PCC process were focused on the steady state optimization. A steady state plant model was first developed and simulated under various conditions such as different solvent concentrations, operating parameters and configurations, better choices which can provide a lower cost for the capture system can then be found through comparisons [6–12].

The steady state model is impossible to represent the dynamics of this process, thus cannot provide enough information for control design. For this reason, much attention has been paid to the dynamic modeling of the solvent-based PCC system . In the first stage, models for standalone absorber and stripper were developed, the behavior of these columns was then tested through dynamic simulations. For example, Lawal and et al. [35] built a dynamic absorber model using both the equilibrium and rate-based approach, and the dynamic simulation showed that the ratio between lean solvent flow rate and flue gas flow rate is critical to maintain the performance of absorber. Ziaii and et al. [36] developed a model for the amine regenerative system, dynamic simulation found that lean solvent loading has key influence on the reboiler temperature. Nevertheless, analysis of the stand-alone columns