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Dynamic Modelling and Controllability Studies of a Commercial-Scale MEA Absorption Processes for CO_2 Capture from Coal-Fired Power Plants

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Abstract

This paper presents a mechanistic dynamic model of an industrial-scale carbon dioxide (CO_2) capture plant using Monoethanolamine (MEA) as an absorbent. In order to remove 87% of CO_2 from the flue gas stream generated from a 750 MW supercritical coal-fired power plant and produce a CO_2 concentration of 95% in the CO_2 product stream, a post-combustion CO_2 capture plant with three absorbers and two strippers are needed,. A decentralized control structure composed of 11 proportional-integral (PI) controllers was proposed to maintain the dynamic operability of this commercial-scale CO_2 capture plant. The evaluation of the plant's performance in closed-loop were conducted using multiple scenarios, i.e., the loss of CO_2 recovery (%CC) control loop during variation of flue gas flow rate, a positive ramp change in the flue gas flow rate under a maximum withdrawal constraint on the reboilers' heat duty, and the disturbance in the flue gas composition resulting from the variation in coal composition and air flow rate. The controllability analysis performed on the proposed industrial-scale MEA absorption plant using the control system designed in this study shows that the plant is able to recover fast from most of the disturbances considered in the analysis. The insight provided from the present study can then be used to address the integration of the present CO_2 capture plant to a coal-based power plant and evaluate the dynamic feasibility of this integration under various scenarios.

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Keywords: MEA absorpsion; Industrial-scale plant; Dynamic modelling; Process control; gPROMS

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1. Introduction

In 2011, 44% of the global CO_2 emissions were from the coal industry, essentially for electricity generation [1]. Due to the characteristics of the flue gas stream produced from coal-fired power plants, i.e., low CO_2 partial pressure and high flow rate, the post-combustion CO_2 capture based on chemical absorption is a suitable technology that can be used to remove the CO_2 from the flue gas stream prior to its release into the atmosphere. Although a post-combustion CO_2 capture plant can be connected to an existing power station with minimal modification in the power plant's facility, no large-scale commercial post-combustion CO_2 capture plant is currently in operation. In order to promote the implementation of an industrial-scale post-combustion CO_2 capture plant, insight regarding the process operability and controllability is needed to ensure the dynamic operability of these plants in the presence of disturbances and uncertainties in the system.

Based on the above, this study aims to present the mechanistic modelling of an industrial-scale CO_2 capture plant using MEA scrubbing process. In addition, a promising multi-loop decentralized control structure is proposed and evaluated using three scenarios which have never been discussed in other open literature. The structure of this paper is as follows: Section 2 provides the description of the industrial-scale CO_2 capture plant using the proposed decentralized control scheme; Section 3 presents an analysis on the plant's performance and capacity using a few scenarios; concluding remarks are presented in Section 4.

Nomenclature

%CC	CO_2 recovery
%flood	Percentage of flooding velocity
IMC	Internal Model Control
Kc	Controller gain
PI	proportional-integral
Q_{reb}	Reboiler heat duty
T_{reb}	Temperature in reboiler
τ_I	Integral time constant

2. Industrial-scale CO_2 capture plant and proposed decentralized control scheme

A mechanistic dynamic model of an industrial-scale CO_2 capture plant presented in this work was scaled up from a pilot plant model developed by the authors [2, 3] and that was based on the experimental data presented by Dugas [4]. The proposed process flowsheet, as shown in Fig. 1, was designed based on two process objectives: (i) achieve the CO_2 removal (%CC) of 87% or higher; and (ii) deliver CO_2 purity of 95% or higher. In order to meet those requirements, the industrial-scale CO_2 capture plant requires of three absorbers (each 11.8 m in diameter and 34 m in bed height) and two strippers (each 10.4 m in diameter and 16 m in bed height). Likewise, the design of other process equipment considered in the CO_2 capture plant was determined based on the design plant capacity, e.g., one-pass shell and tube heat exchanger (3 m in diameter with 6 m in length) and the lean amine flow rate control valve (24 inches in diameter). At the base condition, the flue gas flow rate entering the CO_2 capture plant is 20 kmol/s with 16.3 mol% of CO_2 and it was found that a thermal energy of 4.1 GJ is required to remove one tonne of CO_2 in the flue gas stream. Thus, the plant's CO_2 capture capability is approximately 10,000 tCO_2/day.

Moreover, this study proposed a potential multi-loop control scheme that is similar to that obtained from a previous controllability analysis performed on a post-combustion CO_2 capture pilot plant [3]. As shown in Fig.1, the proposed decentralized control structure is composed of 11 Proportional-Integral (PI) controllers aiming to maintain the plant's operating conditions at specific set points, i.e., %CC is controlled using the flow rate of lean amine entering each absorber (A101, A201, and A301); the reboiler temperature is maintained using reboiler heat duty (Q_{reb1} and Q_{reb2}); and the percentage of opening of the outlet valves (V13, V23, and V33) are used to control the liquid inventory in absorber sump tanks (A102, A202, and A302). In order to obtain fast and smooth dynamic responses, the controller tuning parameters proposed in this work, i.e., controller gain (K_c) and integral time constant

(τ_I), were tuned using the Internal Model Control (IMC) method [5] and the sequential loop tuning method proposed by Hovd and Skogestad [6]. The performance of the proposed control scheme for the industrial-scale CO_2 capture plant is presented next.

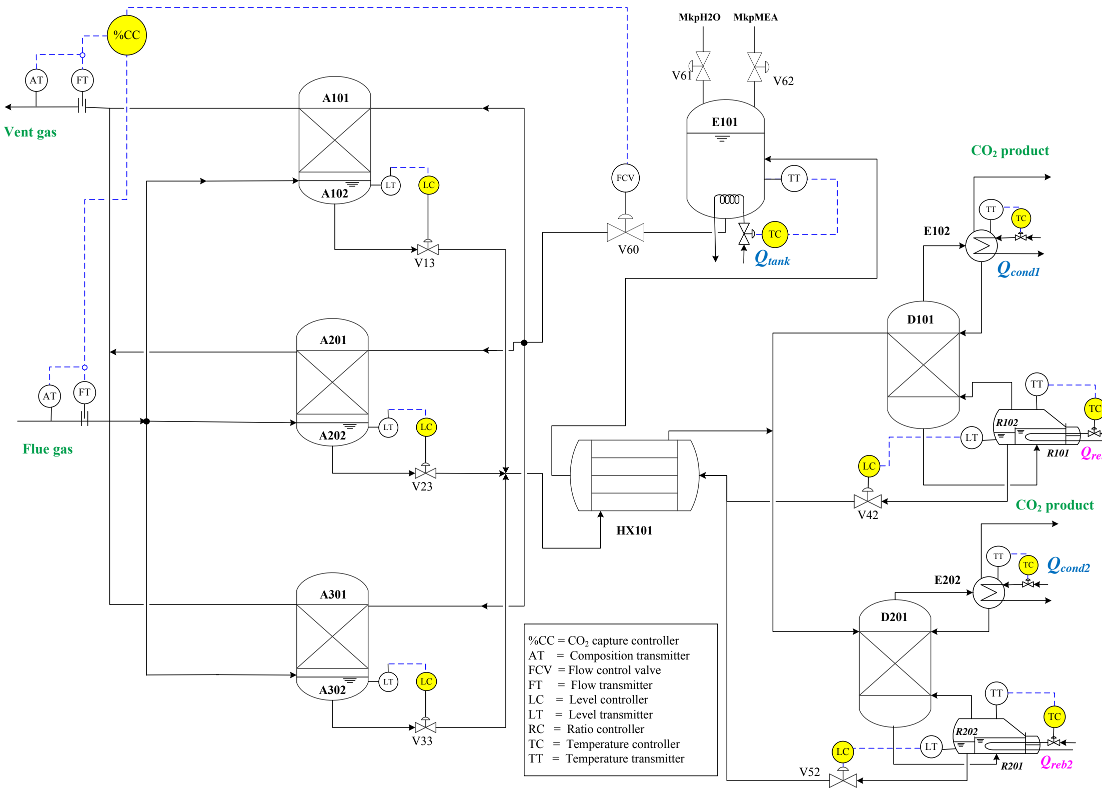

Figure 1 Flowsheet of the commercial CO_2 capture plant.

3. Evaluation of plant's performance

This section presents the performance of the commercial-scale CO_2 absorption plant using the proposed control strategy shown in Fig. 1. This dynamic model was tested under following scenarios: *(i)* change in flue gas composition, *(ii)* loss of CO_2 recovery control loop during variation in the flue gas flow rate, and *(iii)* ramp change in flue gas flow rate under the limitation of the reboiler heat duty. Additional scenarios while using this plant are presented elsewhere [7]. The performance evaluation using each scenario is described next.

3.1. Flue gas composition

Based on the fact that the flue gas composition may fluctuate due to the variation in coal composition and air flow rate fed to the furnace, this test, thus, aims to study the effect of the change in flue gas composition on the plant's performance. To mimic the actual scenario of changes in flue gas composition in actual power plant, a sinusoidal disturbance in oxygen (O_2) and CO_2 flow rates were introduced to the plant at the second hour of operation. As shown in Fig. 2.a, the CO_2 flow rate in the flue gas stream varied in the range of ±2.4% of nominal flow rate over the course of 28 h. Also, the variation in the oxygen's flow rate, approximately ±1.1% of normal condition, had been continued for 40 h. As a result, the variation in the total flue gas flow rate can be observed during 2 h to 42 h of the operation, presented in Fig.2.b. This figure also shows the response in %CC during the variations in CO_2 and O_2 flow rates. As shown in that figure, the response in %CC is oscillatory and showed relatively slight variation at the 31^{st} hour, when the sinusoidal change in CO_2 flow rate was stopped while that of O_2 flow rate continued for the rest of the test. The variation in %CC due to given process disturbance was, however, minimal, about ± 0.7% of the nominal %CC value (87%CC). Therefore, the result of this test indicates that the CO_2 capture plant is able to maintain the CO_2 recovery performance closed to its set point in the presence of changes in the CO_2 and O_2 composition in the flue gas stream.

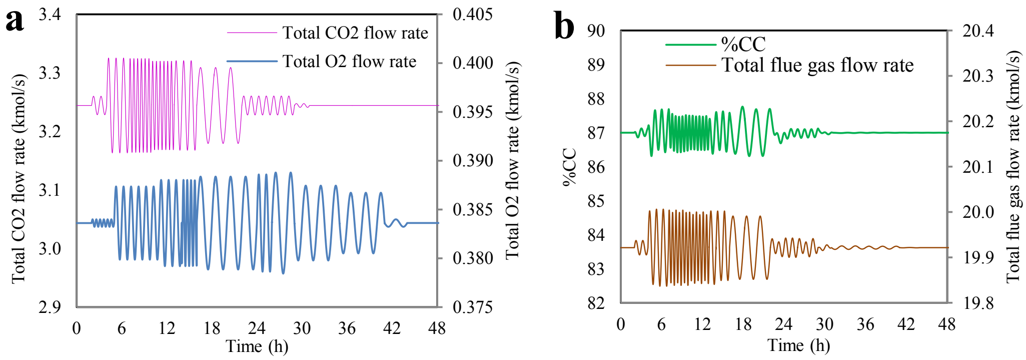

Figure 2 Process responses to change in flue gas compositions: (a) CO_2 and O_2 flow rate in flue gas stream; (b) CO_2 recovery and total flue gas flow rate.

3.2. Loss of %CC control loop during variation in the flue gas flow rate

This scenario aims to investigate the plant's performance when the %CC controller is offline for a period of time while the flue gas flow rate is varying. During the first six hours of this test, a sinusoidal change in the flue gas flow rate (± 2.5%) was introduced to the plant; as a result, the CO_2 recovery (%CC) varied in the range of 86.2% to 87.9% (±1% of nominal value) as shown in Fig.3.a. At the sixth hour, valve V60 has been stuck at the percentage of opening of 29.4% for 4 hours prior to resuming its function at the 12^{th} hour. Fig. 3.a shows that, while V60 is stuck, the range of %CC (85.2% to 87.4%) was slightly lower than that at the normal operation. The change in the percentage of flooding velocity (%flood) in absorber (A101) is also minimal. On the other hand, as shown in Fig. 3.b, the %flood in stripper (D101) was almost constant at 61% since the amine circulation rate remained unchanged due to V60 stuck at the position of 29.4% opening. Note that A101 is used to represent the other two absorbers, A201 and A301, since they have the same design. Likewise, the condition in D101 is the same to that in D201. This test indicates that the CO_2 capture plant is able to maintain the %CC closed to its set point although the lean amine control valve is stuck at a certain position for a certain period of time.

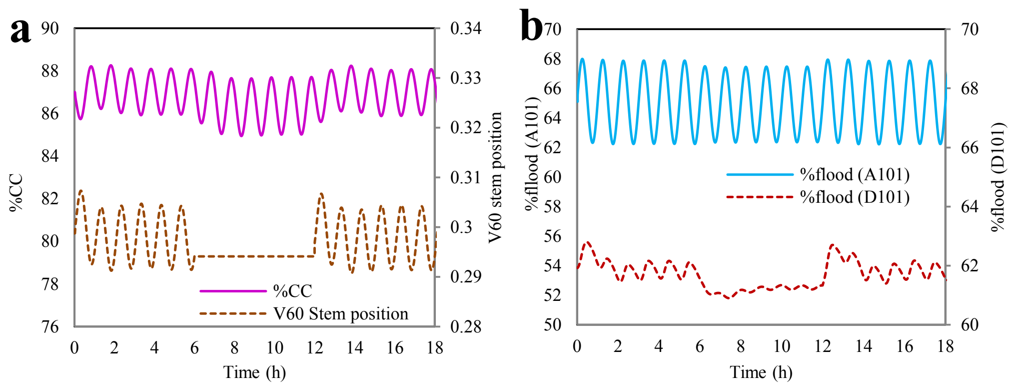

Figure 3 Process responses to the loss of %CC controller during variation in the flue gas flow rate: (a) CO_2 recovery and V60 stem position; (b) %flood at A101 and D101.

3.3. Ramp change in flue gas flow rate under the limitation of the reboiler heat duty

The objective of this test is to gain insight on the plant's performance when the reboiler heat duty reaches a given upper constraint set for this case study to 307 MW, which is 20% above the normal heat duty (256 MW). In this scenario, a positive ramp change of 20% in the flue gas flow rate with respect to its nominal (base case) flow rate (20 kmol/s) has been introduced to the plant at the tenth hour of the operation and last for up to three hours. As shown in Fig. 4.a, the plant seems to be able to return the %CC set point as the %CC trend goes up during the 13th to 14th hour; however, the plant cannot attain the CO_2 recovery of 87% since the reboiler heat duty (Q_{reb}) reaches the maximun constraint at the 14th hour (see Fig. 4.b). As shown in Fig. 4.c, the V60 valve acts so that it aims to return %CC to its set point; nevertheless, the lean MEA stream flowing to absorption process most likely contains high CO_2 content because the reboiler heat duty has already reached its saturation limit. That is, the lean amine is not lean anymore. As a result of high MEA solution circulation rate due to the opening of V60 and a maximum withdrawal constraint on the reboiler heat duty, the temperatures of the amine solution in the reboilers (T_{reb1} and T_{reb2}) are significantly reduced (see Fig. 4.b). Moreover, the large amounts of MEA solution being circulated in the plant causes an increase in %floods in both the absorbers and strippers units, as shown in Fig. 4.d. Based on the results obtained from this test, the CO_2 capture plant is not able to maintain the desire %CC when the required reboiler heat duty is higher than the available heat duty source.

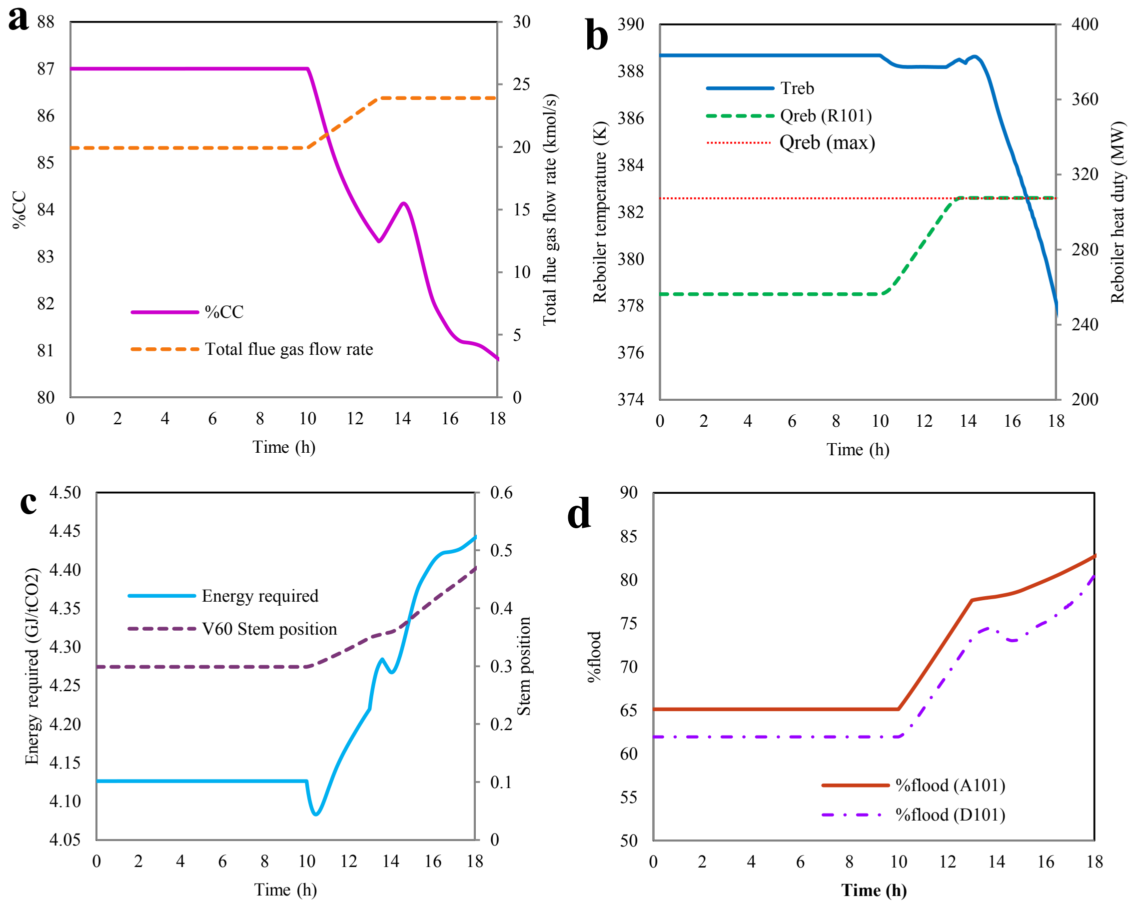

Figure 4 Process responses to changes in flue gas compositions.

4. Conclusions

The dynamic operation of an industrial-scale CO_2 capture plant for 750 MW supercritical pulverized coal-fired power plants has been presented in this work. To maintain the operation of the plant on target and within its feasible limits, this study proposed a multi-loop decentralized control scheme using 11 PI control loops, and conducted the evaluation of the plant's performance in closed-loop under various scenarios. In the case of changes in the flue gas compositions, this study shows that the CO_2 capture plant's design is able to accommodate the disturbance in the flue gas compositions resulting from the variation in coal compositions and air flow rate. Furthermore, in the case where the %CC control loop was lost due to a malfunction of a measurement device in that loop and the variation in the flue gas flow rate occurred simultaneously, the analysis shows that the plant can still continue the operation, thus providing a period of time for plant troubleshooting. However, the percentage of CO_2 recovery during the loss of %CC controller may slightly deviate from the desired %CC set point since the lean amine flow rate control valve cannot be adjusted during this period, which results in a loss in plant's performance. In addition, this study shows the system's response when a positive ramp change in the flue gas flow rate was introduced to the CO_2 capture plant under a maximum withdrawal constraint on the reboiler heat duty. Analysis of this scenario can be used to improve the control system, for instance, additional equipment should be included in the plant, e.g., a flue gas flow rate controller and a flue gas vent line, to ensure that the flue gas flow rate entering the CO_2 capture plant is lower than that maximum plant capacity.

According to the controllability analysis described in this paper, this industrial-scale plant using the proposed control scheme shows smooth process responses with small oscillations and maintains key control variables at their desired set points. The insight of an industrial-scale CO_2 capture plant and process controllability gained from this study can be used for future studies, i.e., the integration of the existing fossil-fired power plants with a CO_2 capture plant and a CO_2 compression train, and a study on the reduction in energy consumption for MEA regeneration.

Acknowledgements

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