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Dynamic modeling and validation of post-combustion CO_2 capture plants in Australian coal-fired power stations

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Abstract

Flexible operation of post-combustion CO_2 capture (PCC) plants can improve efficiency through coordinating the balance between consumer demands for electricity and CO_2 emission reductions. This strategy however, will impose process disturbances while the PCC plant is ramped up, ramped down or turned off. This paper presents the preliminary development of a dynamic model for PCC in a brown coal-fired power plant using the process simulation software Aspen Plus Dynamics. Validation of the dynamic model will be against both steady state and dynamic data from the pilot plant. By gaining this understanding of the dynamic behavior, the technical and financial performance of PCC can be optimised.

Keywords: Dynamic process modelling; flexible operation; post-combustion CO_2 capture; coal-fired power stations; process optimisation, model validation

Nomenclature and Abbreviations

PCC	post-combustion CO_2 capture
CO_2	carbon dioxide

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GHG	greenhouse gas
CCS	CO_2 capture and sequestration
SO_X	sulphur oxide
NO_X	nitrogen oxide
FGD	flue gas desulphurisation
$deNO_X$	denitrification
ABS	absorber
FPT	flue gas pre-treatment
ABS-T01	temperature sensor 01 on the absorber column
FPT-T03	temperature sensor 03 on the flue gas pre-treatment column

1. Introduction

Fossil-fuelled power generators produce one quarter of the global greenhouse gas (GHG) emissions in terms of CO_2-equivalent emissions, where carbon dioxide (CO_2) contributes 80% of total GHG emission [1]. The combustion of brown coal emits more CO_2 compared to the dominant fossil fuels [2]. The majority of electricity worldwide is generated from coal due to its wide availability, stability of supply and low cost [3]. In Australia, coal-fired power plants supply 86% of the country's electricity [4].

Subsequently, significant reductions in GHG emissions can be achieved through CO_2 capture and sequestration (CCS) from existing fossil-fuelled power stations. The strong motivation to continue development and deployment of clean energy and CO_2 capture has resulted in a number of CCS demonstrations worldwide [5]. The International Energy Agency (IEA) has indicated that CCS will play a vital role in reducing CO_2 emissions to half of 2005 levels by 2050 [5].

One conventional strategy for CO_2 capture from coal-fired power stations involves the use of various solvents for absorption from flue gas. In fact with a number of PCC pilot plants around the world, the development of amine-based solvent for post-combustion CO_2 capture (PCC) has advanced considerably. Shown in **Error! Reference source not found.**, PCC is suitable for retrofit to existing fossil fuel-fired power plants and has the capacity to treat flue gas streams with low CO_2 partial pressure [6, 7]. The major drawback of PCC is the large energy requirement, as well as the high capital and operational cost. Additionally, amine-based PCC solvents are susceptible to chemical degradation by sulphur oxide (SO_X) and nitrogen oxide (NO_X) present in flue gas. Degradation will decrease the CO_2 absorption capacity of the solvent, which consequently results in higher cost of electricity [8, 9]. In Australia, the lack of legislative requirements for flue gas desulphurisation (FGD) and denitrification ($deNO_X$) units in power plants results in further capital and operating expenses [10].

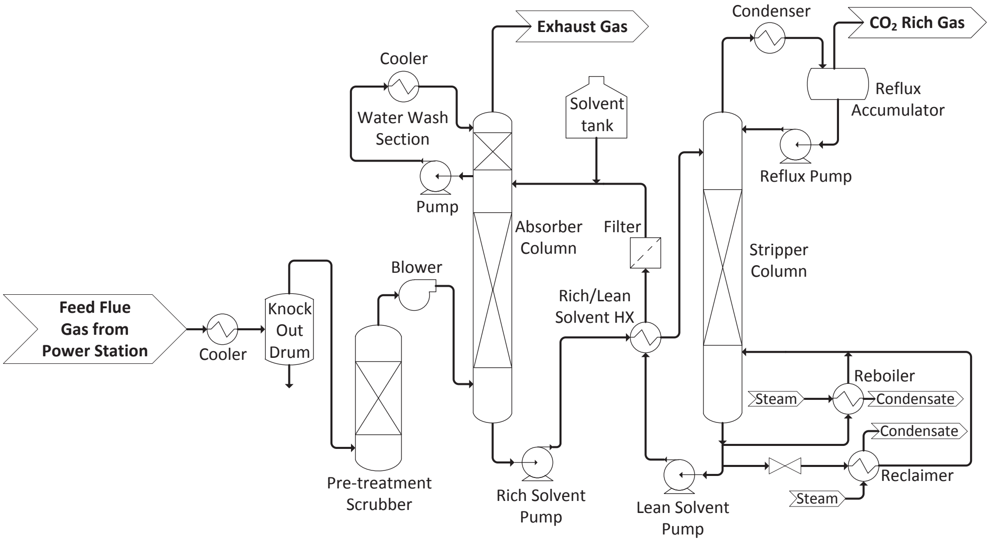

Fig. 1. The post-combustion CO_2 capture process including the pre-treatment of flue gas to remove particulates and neutralise contaminants such as SO_X and NO_X, required under Australian condition.

Flexible operation of PCC is one approach which has been proposed as a means of addressing the energy penalty during peak periods for electricity demand. For periods of low energy demand, electricity prices will be lower and capture rates may be ramped up accordingly. Conversely, electricity prices will be higher during high demand periods, thus capture may be turned down or switched off completely [11]. Therefore, flexible capture plant operation minimizes the parasitic load on the power plant at crucial periods in the energy market and maximizes financial performance. Flexible operation of CO_2 capture imposes process disturbances and further investigation of dynamic behavior is required. Further detail of other flexible operation strategies are discussed in the methodology section.

The paper presents the initial development of a dynamic model of the CO2 absorption process in a brown coal-fired power plant with the process simulation software Aspen Plus Dynamics. Through studying the dynamic behavior of the CO2 capture process, the process can be optimized for flexible PCC operation under Australian conditions to maximize technical and financial performance.

2. Methodology

2.1. Development of Dynamic PCC Model

The dynamic model of the CO_2 absorption process in a brown coal-fired power plant is under development using the process simulation software Aspen Plus Dynamics. The preliminary results from the model are based on the specifications of the CSIRO PCC pilot plant located at the Loy Yang brown coal fired power station in Victoria’s Latrobe Valley, Australia. The PCC pilot plant is operated by CSIRO, consisting of a gas pre-treatment and cooling column, two absorption columns and one stripper column, where Pall ring packing is used in all columns. The pre-treatment column is a caustic wash column for cooling, conditioning and removal of SO_X, NO_X and particulate.

The validation of the dynamic PCC model for both steady state and dynamic cases is being undertaken using data from the PCC pilot plant. This involves the verification of model predictions against pilot plant data for CO_2 loading at various points and temperature profile in all columns. Validation will demonstrate the accuracy and reliability of model predictions. The reconfiguration and optimization of the validated dynamic CO_2 capture process model for flexible operation are under investigation, discussed further in the next section.

2.2. Flexible Operation Strategies

The development of novel flexible operation strategies to improve process performance and reduce the environmental impact of brown coal power generation will be undertaken using an optimized dynamic PCC model. The investigation will also identify key components and equipment within PCC process that have a significant influence on the process performance during flexible operation.

One flexible operation strategy is to use different operation modes such as partial capture, part-time capture or variable capture, these are summarized in **Error! Reference source not found.**. The flexible operation mode and capture rate percentage is selected based on the trends in the electricity demand. Another approach to flexible PCC operation is to configure the CO_2 capture plant by incorporating a bypass system or solvent storage tanks. Solvent regeneration for PCC requires heat that is sourced from steam that has been diverted from the steam turbine in the power plant. However, steam extraction would lengthen the start up and shut-down times of the power plant [12]. Therefore, it is necessary to include a system that allows feed flue gas to bypass the entire PCC process and vents excess flue gas, ensuring operation of the power plant is independent of the PCC process [13]. An alternative bypass system is shown in **Error! Reference source not found.** (a), where a bypass valve within the PCC process redirects the rich solvent back to the absorber. The result is a decrease in CO_2 capture and increase in power plant output [14], providing additional flexibility for periods of high electricity demand.

The addition of a solvent storage system can further improve the flexibility of the PCC process. The solvent storage system in **Error! Reference source not found.** (b) consists of two storage tanks. When power prices are high, rich solvent exiting the absorber is stored in one tank while lean solvent stored in the other equally-sized tank is utilized for CO_2 absorption. When electricity demand is low, stored rich solvent is regenerated in the stripper and lean solvent exiting the stripper accumulates in the other storage tank [3, 14, 15].

Table 1. Operation strategies for flexible operation of a post-combustion CO_2 capture plant.

Operation Mode	CO_2 Capture Rate %	Description
Full time complete CO_2 capture	One capture rate >90%	Full time capture with a constant CO_2 capture rate.
Partial CO_2 capture	One capture rate <90%	Full time capture of CO_2 at constant recovery rate, residual portion of CO_2 is vented with exhaust flue gas.
Part-time CO_2 capture	One capture rate One CO_2 capture percentage	Capture is on for selected intervals of time when electricity demand is low. CO_2 capture is off when electricity demand is high and flue gas is vented
Variable CO_2 capture	Multiple capture rate percentages	Different CO_2 capture rate percentages for selected time intervals allocated based on the trends electricity demand, capture plant is built to capacity specifications

	of the maximum capture rate

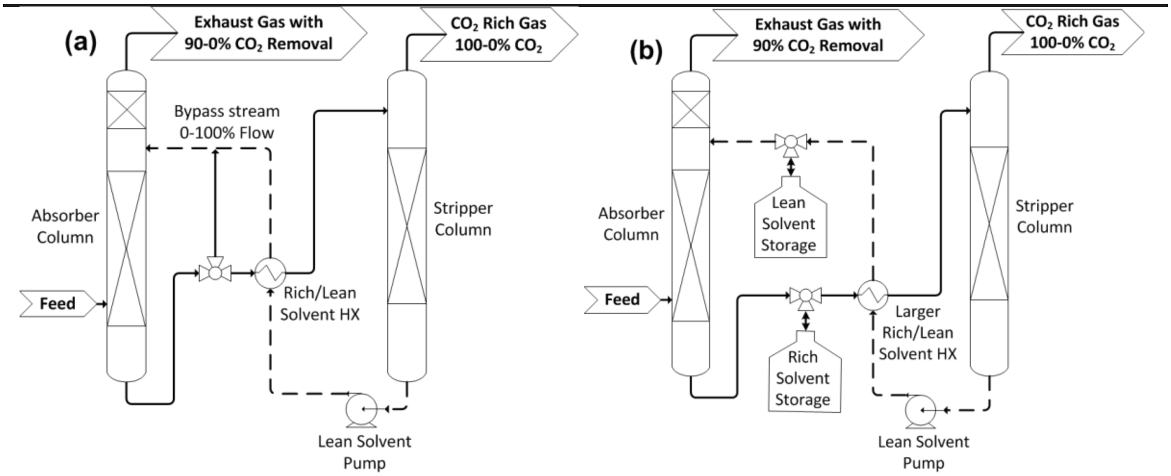

Fig. 2. Flexible operation strategies for a PCC plant can involve the integration of (a) a bypass system or (b) solvent storage tanks.

The optimal operation strategy can be determined by implementing each of these flexible operation strategies into the dynamic model. Evaluation of the flexible PCC model will be based on both economic and technical factors.

3. Preliminary Results and Discussion

Dynamic process models of CO_2 capture systems are usually only validated with steady state pilot plant data as there is a general lack of dynamic pilot plant data available [6, 16-23]. Most pilot plants are typically operated at steady state and not equipped for collecting consistent dynamic data. The major problem with collecting dynamic data is the reproducibility difficulties during these transient periods of pilot plant operation (i.e. start-up or shut down).

The CSIRO pilot plant at Loy Yang Power uses sensors to monitor flow rate, pressure and temperature throughout the entire plant. The pilot plant does not have sensors fitted for simultaneous online measurements of CO_2 loading at various points in the process. Instead, solvent is sampled at various points in the pilot plant during steady state operation and a liquid analysis provides CO_2 loading readings. The GASMET gas analyser provides measurement of gas composition. The pilot plant absorber column temperature profile in **Error! Reference source not found.** demonstrates that even at "steady state" operation where flue gas flow rate is constant, there will be significant fluctuations in temperature, pressure and flow rate. Therefore, "steady state" operation of the pilot plant operation is technically always dynamic, suggesting process plant operation is never truly a constant value steady state.

Obtaining reproducible steady state pilot plant data can be challenging since steady state operation is difficult to maintain due to changes in ambient temperature and CO_2 concentration of the feed flue gas. Consequently, the data collection for dynamic pilot plant behaviour will be a challenge due to technical obstacles and data reproducibility issues. Additionally, dynamic pilot plant data measurements will need to account for time variation. One key process parameter is residence time for individual equipment [24], which in turn has a significant influence on the response time of the system to parameter changes.

Therefore when considering all of these factors, it can be anticipated that the procedure for collecting reproducible dynamic data will need a considerable amount of time to fine tune and perfect.

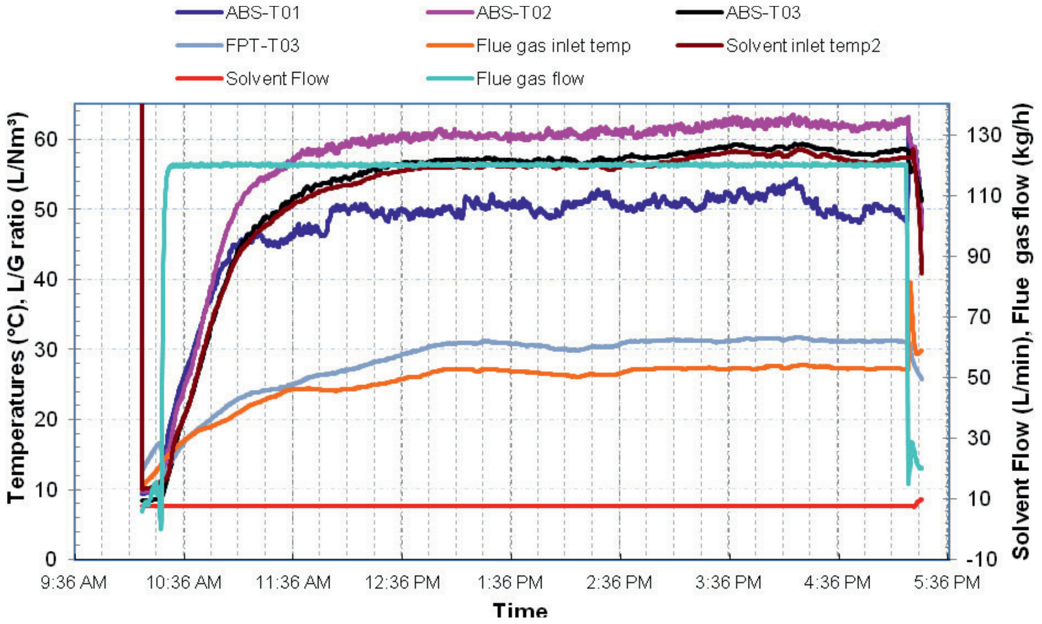

Fig. 3. Temperature profile of absorber column 2 at the CSIRO PCC pilot plant at Loy Yang Power on the date of 13 August 2012. The temperature transmitters (ABS-T01 to ABS-T02) are at various points on the absorber column; FPT-T03 is the temperature of the flue gas exiting the pre-treatment process. Note the scale for solvent flow and exit CO2 gas flow is on the right hand side.

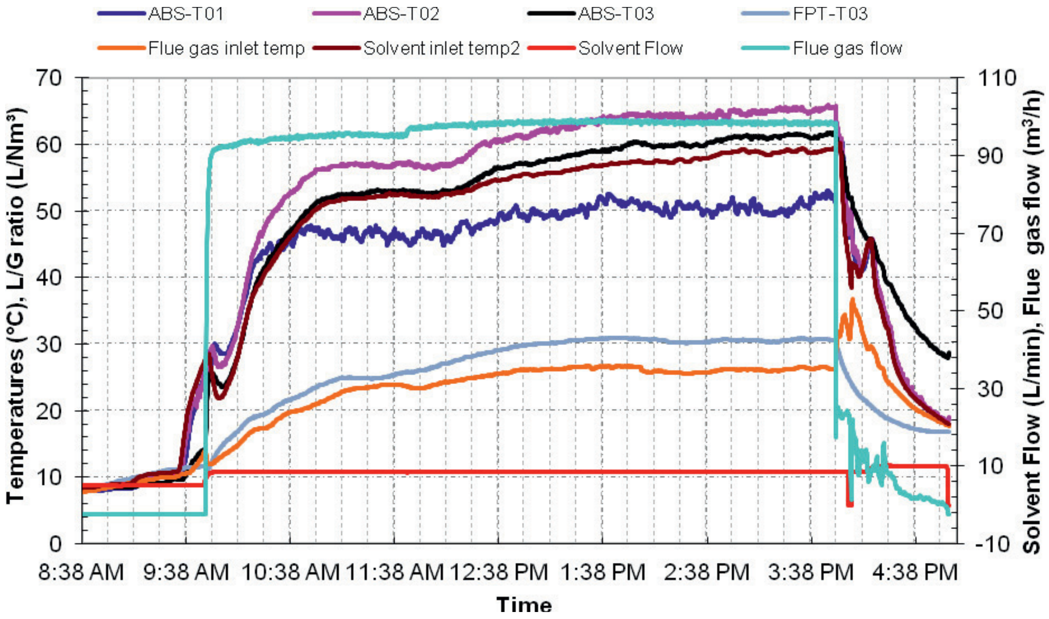

Fig. 4. Temperature profile of absorber column 2 at the CSIRO PCC pilot plant at Loy Yang Power on the date of 2 August 2012. The temperature transmitters (ABS-T01 to ABS-T02) are at various points on the absorber column; FPT-T03 is the temperature of the flue gas exiting the pre-treatment process. Note the scale for solvent flow and exit CO2 gas flow is on the right hand side.

Error! Reference source not found. shows the effect of changing flue gas flow from 120 kg/h to 122 kg/h (at 11:45 AM) in the CSIRO PCC pilot plant at Loy Yang. The pilot begins at steady state and upon increasing the flue gas flow, the temperature began to increase in the absorber suggesting that the process is sensitive to flow changes. For this case, the response time of the CO_2 capture process to the change in flue gas flow was approximately 20 minutes. However, an additional 40 minutes was required for the system to reach steady state. This suggests that the total time required for the system to reflect a change in flue gas flow is 60 minutes. The lag in response time can be attributed to the solvent passage and mixing time of equipment (e.g. columns, feed tank and knock out separation tanks).

The "snapshots" approach to modelling dynamic behaviour using a steady state process simulation program was proposed by Gruber (2004) [25]. A similar approach can be applied to pilot plants to obtain consistent and reproducible dynamic data. After making small step changes to a flow rate parameter (i.e. either flue gas or solvent flow), the pilot plant is allowed to reach steady state. Temperature, pressure, CO_2 loading and concentration at steady state can be measured after each change in flow rate. The dynamic behaviour of the pilot plant is demonstrated by plotting these variables against the step changes in flow rate. As noted from **Error! Reference source not found.**, the step-wise procedure would require a time interval of at least 60 minutes between each measurement.

4. Conclusion

The preliminary pilot plant data supports and suggests that the proposed step-wise procedure for collecting dynamic data has validity. The pilot plant used for this study has a response time of 20 minutes when a change is made to flue gas flow. Also, upon making a flue gas flow change, the pilot plant requires at least 60 minutes to reach steady state. The effect of successive step-wise changes to flue gas flow and solvent flow, as well as result reproducibility is under further investigation. This study will contribute to the development of a procedure for dynamic data collection from pilot plants. The validation of dynamic models with dynamic pilot plant data will be a significant contribution towards improving our understanding of dynamic behaviour in PCC plants. Furthermore, the validated dynamic model will be an essential tool to evaluate the feasibility of flexible operation in PCC plants.

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