Proceedings of the 6th International Conference on Process Systems Engineering (PSE ASIA)
25 - 27 June 2013, Kuala Lumpur.

# Dynamic Simulation and Control of MEA Absorption Process for $CO_2$ Capture from Power Plants

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## Abstract

MEA absorption process is an approach for mitigation of $CO_2$ from flue gas that produces from power plant. $CO_2$ capture process is an inherent dynamic system that is affected by the variations occurring in the operating conditions of the power plant. A dynamic model for the complete MEA absorption process was developed to study the operability of this process in a dynamic fashion. A basic feedback control strategy based on Proportional-Integral (PI) controllers was developed and implemented using this dynamic model to study the closed-loop performance of this system under the effect of external perturbations. In order to achieve the main objective of $CO_2$ capture process and to satisfy the temperature constraint in the reboiler unit, the percentage of $CO_2$ absorbed in the absorber column and reboiler temperature were selected as the controlled variables in the present control strategy. The PI controllers tuning parameters were initially obtained using the Internal Model Control (IMC) method. The closed-loop performance of the process was improved by manually tuning the PI controllers using process knowledge and heuristics. The closed-loop test for disturbance rejection conducted in this study showed that the MEA process remained stable in the presence of changes in the flue gas flow-rate and comply with the controllability goals specified for this process.

**Keywords**: Dynamic simulation; Process Control; $CO_2$ capture; MEA absorption process; Fossil fuel power plant.

## 1. Introduction

$CO_2$ capture from fossil fuel power plants using amine-based solvents, typically monoethanolamine (MEA), is one of the most promising technologies for the abatement of $CO_2$ gas. $CO_2$ removal by MEA absorption process has been extensively studied to optimize the process operating conditions (Abu-Zahra et al., 2007; Alie et al., 2005; Freguia and Rochelle, 2003), to improve or test new solvents and to propose new designs that minimize energy consumption (Oyenekan and Rochelle, 2007; Van Wagener and Rochelle, 2011) and reduces plant efficiency loses. Most of these studies describe the behaviour of this process using steady-state models, i.e., those studies assume that the power plant operates continuously at a given base load. However, power plants are subject to start-up, shut-down and changes in the flue gas load due to fluctuations in electricity demands. Figure 1 shows a typical output from coal power generation plants in Ontario, Canada. As shown in this Figure, the output of the boilers varies from 1900 to 3100 MW over the course of a day. This data shows that the operating conditions of the power plant changes significantly in one day of operation. The flow rate of the flue gas from the boilers, and the corresponding amount of $CO_2$ released from flue gas, will also change in a similar fashion.

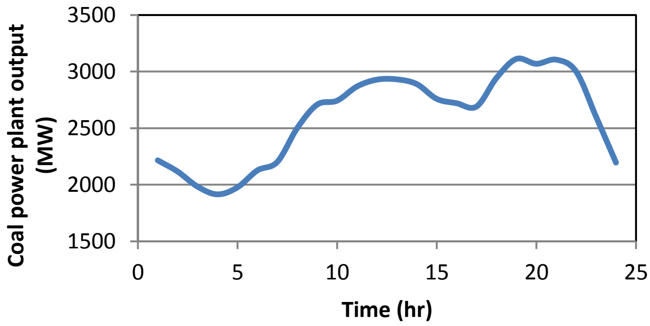



**Figure 1.** A typical output from coal power generation plants in Ontario, Canada (IESO, 2011)

Although valuable insight can be obtained from a steady-state analysis, the steady-state simulation is not sufficient to study the operability of the power plant with $CO_2$ capture. A complete understanding of the dynamic operability of the power plant with $CO_2$ capture using amine scrubbing is fundamental to successfully implement this process in commercial scale power plants. A comprehensive mechanistic first principle dynamic model for the complete MEA absorption process was developed to study the operability of this process in a dynamic fashion (Harun et al., 2012).

The aim of this study is to develop a relative simple decentralized control configuration that maintains the $CO_2$ absorbed and the reboiler temperature within their desired set point values when changes in the flue gas flow rate, which is the disturbance selected for this controllability study, enter the $CO_2$ capture process. The Proportional-Integral (PI) controllers tuning parameters were initially obtained using the Internal Model Control (IMC) method. The main advantage in the present analysis is that the process insight obtained from the mechanistic process model can be used to design the controllers that will be included in the control structure configuration, i.e., a model-based control strategy can be used to estimate the controller tuning parameters.

## 2. Control Structure Design

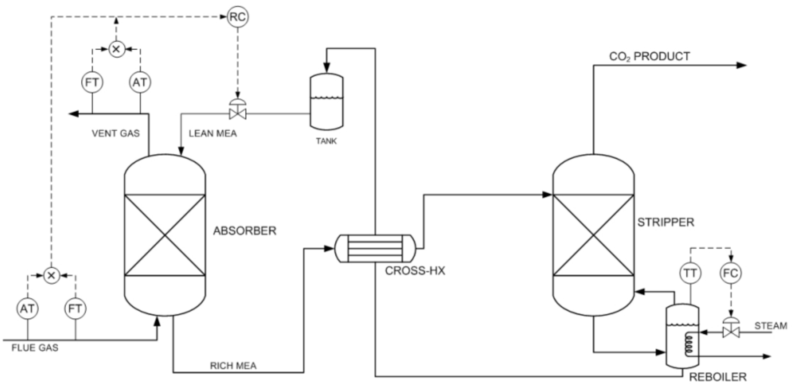
The main objective of a $CO_2$ capture process plant is to reduce the $CO_2$ emissions from the fossil fuel combustion power plant to meet the environmental specification. The percentage of $CO_2$ absorbed, which determines the amount of $CO_2$ in the vent gas that is released to the atmosphere, can be considered as a key variable that needs to be controlled for this process. Moreover, the temperature in the reboiler unit needs to be below 120$^o$C to avoid thermal solvent degradation but at the same time it is desired to operate the reboiler at a high temperature to provide enough heat for the solvent regeneration in the stripper column.

One variable that can be adjusted to control the operation of this process is the reboiler heat duty. This process variable can be potentially used as the manipulated variable to control the changes in the reboiler temperature which has a direct effect on the reboiler temperature. Also, the reboiler heat duty has also been proposed by previous control studies to control the reboiler temperature, e.g., Lawal et al. (2010) and Lin et al. (2011). The other input variable that can be considered as manipulated variable is the valve stem position that regulates the amount of lean liquid solvent flow rate that enters at the top absorber column. The absorption of $CO_2$ in the MEA solution relies on the reaction between the $CO_2$ and the MEA in the absorber unit. As lean solvent flow rate is increased, more MEA is available to react with the absorbed $CO_2$ thus increase the absorption of $CO_2$ in the liquid phase of the absorber column. The previous control studies of the MEA absorption process published in the literature also manipulate the lean solvent flow rate to control the percentage of $CO_2$ absorbed in the absorber column (Lawal et al., 2010; Lin et al., 2011).

Figure 2 shows the proposed control structure for $CO_2$ capture process in this study. The percentage of $CO_2$ absorbed is determined by simultaneously measuring the $CO_2$ flow rate in the flue gas and in the vent gas. The ratio of $CO_2$ flow rate between these two streams was calculated and transmitted to the ratio controller as controller input. The $CO_2$ ratio was calculated using following equation:

$$\text{Ratio}=\frac{CO_2 \text{ flow rate in vent gas}}{CO_2 \text{ flow rate in flue gas}} \qquad 1$$

The ratio controller output's signal is transmitted to the process so that the lean solvent flow rate is changed by manipulating the valve stem position so that the percentage of $CO_2$ absorbed is maintained near its set point (desired) value.




AT: Composition transmitter, FT: Flow transmitter,
TT: Temperature transmitter, RC: Ratio controller FC: Flow controller

**Figure 2.** The proposed control structure for $CO_2$ capture process

Based on the pairings between the manipulated and controlled variables selected for this process, a sensitivity analysis between these variables was conducted to determine meaningful tuning parameters for each of the PI controllers considered in the closed-loop system shown in Figure 2. The controlled variables' response to the manipulated variables was approximated to a first-order linear model so that the process gain ($K_p$) and the time constant ($\tau_p$) of the process can be determined. The averaged of these process model parameters were used to determine the initial PI controller tuning parameters using the IMC method.

## 3. Control strategy implementations

Using the control configuration proposed in this study, a series of closed loop dynamic simulations were performed in the system to study the performance of the control system in response to changes in the disturbance. The disturbance investigated in this work was the flue gas flow rate.

*Ramp change in the flue gas flow rate*

The flue gas flow rate was increased (decreased) linearly by 10% within 2.8 hrs of operation and remained at that condition for about 8 hrs. Figure 3 shows the percentage of $CO_2$ absorbed in the absorber column when a $\pm$10% ramp change in the flue gas flow rate was considered in the analysis. As shown in this Figure, the percentage of $CO_2$ absorbed was slightly decreased (increased) at the onset of the disturbances. Due to the PI feedback controller action, the lean solvent flow rate linearly increased (decreased) as depicted in Figure 4. The lean solvent flow rate was increased by 16% and decreased by 13% from its initial steady state condition due to the changes in valve stem position, respectively. As the flue gas flow rate was increased, more lean solvent was required to react with $CO_2$, so that the amount of $CO_2$ absorbed can be maintained. The opposite behaviour was observed when the flue gas flow rate was reduced using a change of type ramp.

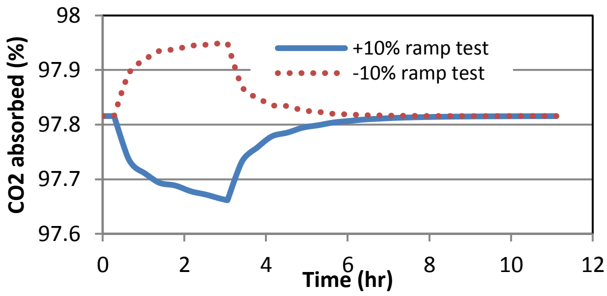



**Figure 3.** The percentage of $CO_2$ absorbed during disturbance rejection test

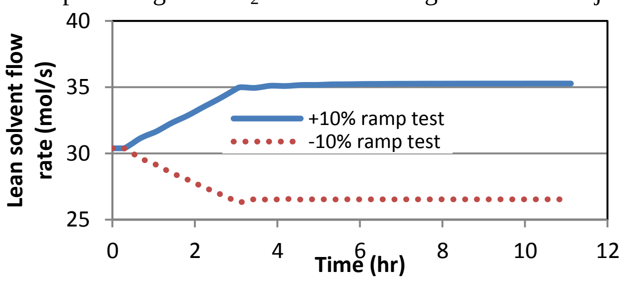



**Figure 4.** Lean solvent flow rate during disturbance rejection test

The responses shown in Figure 5 illustrate the behaviour of the reboiler temperature when ramp changes in flue gas flow rate were induced. As shown in this Figure, the reboiler temperature was slightly decreased (increased) at the start of disturbance tests. Small changes in the reboiler temperature were observed due to vaporization of MEA solution at this operating condition. In order to confirm this result, steady simulations using standalone flash model in Aspen Plus® were conducted (Harun, 2012). It was found that the difference between the temperature estimated using the gPROMS model and Aspen Plus® was less than 0.4%. This result confirms the gPROMS model developed in this work. Due to the changes in the flue gas flowrate, the manipulated variable, which is the reboiler heat duty, was slightly increased by a magnitude of 20% (decreased with magnitude of 16%) from the nominal operating conditions to compensate for this error until the reboiler temperature reaches the set point value after 6 hours of operation (See Figure **6**5). Even though small changes in the reboiler temperature was observed, a significant amount of heat supplied from the reboiler used to vaporize the MEA solution.

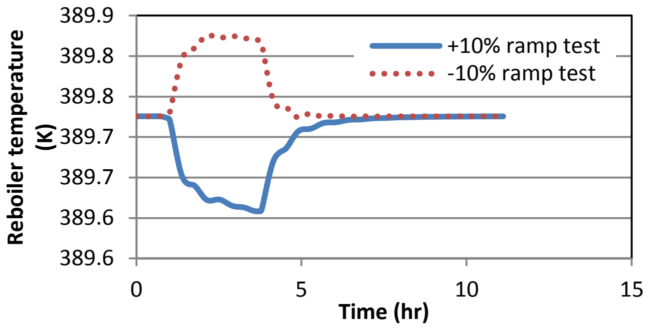



**Figure 5.** Reboiler temperature during disturbance rejection test

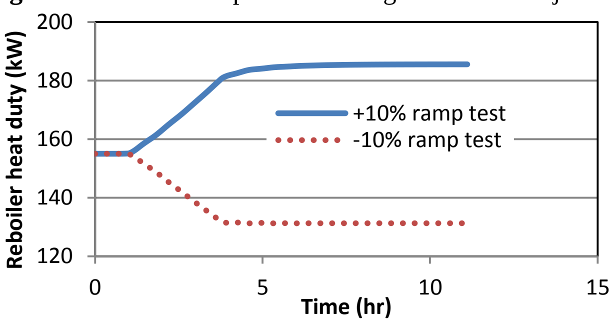



**Figure 6.** Reboiler heat duty during disturbance rejection test

The closed-loop tests conducted in this study showed that the MEA process remained stable in the presence of changes in the flue gas flow-rate and comply with the controllability goals specified for this process. Thus, it shows that the control strategy developed in this work is a promising control structure that can be used to control the key process variables in the MEA $CO_2$ capture process

## 4. Conclusions

The control structure developed in this work was developed using a basic feedback control strategy. However, there are several controllability aspects that can also be considered for the MEA process in the future. For example, a new control strategy can be developed that can take into account the saturation limits on the amount of heat that can be supplied to the reboiler unit and the addition of new control objectives within the analysis such as the quality of the $CO_2$ leaving the stripper column. Also, a centralized control strategy based on Model Predictive Control (MPC) can be proposed and compared to those based on traditional feedback controllers (decentralized strategies) to determine the most suitable control strategy for this process.

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