

# Dynamic modelling and control of a pilot plant for post-combustion CO<sub>2</sub> capture

Grégoire Léonard,<sup>a</sup> Bruno Cabeza Mogador,<sup>a</sup> Ségolène Belletante,<sup>a,b</sup> Georges Heyen<sup>a</sup>

<sup>a</sup>*Laboratory for analysis and synthesis of chemical systems, University of Liège, Allée de la chimie B6a, 4000 Liège, Belgium*

<sup>b</sup>*ENSIACET, Allée Emile Monso 4 BP 44362, 31030 Toulouse Cedex 4, France*

## Abstract

A dynamic model of a post-combustion capture pilot plant is developed using Aspen Plus Dynamics. An innovative process control strategy is studied for regulating the water balance of the process. A washing section where the flue gas from the absorber is washed with cold water is included to the process in order to reduce the emissions of amine to the air. Control of the water balance in the solvent loop is successfully achieved by changing the washing water temperature. In previous publications regarding CO<sub>2</sub> capture pilot plants, the regulation of the water balance always required a water make-up flow which appears here as unnecessary. Rejection of disturbances and different load reduction scenarios are tested to confirm the efficiency of this strategy. Potential operational problems of this control strategy are identified and solved.

**Keywords:** CO<sub>2</sub> capture, reactive absorption, dynamic modelling, control strategy.

## 1. Introduction

The combination of growing energy demand and environmental concerns has made the development of CO<sub>2</sub> capture and storage technologies a necessity for the near-future energy mix. Post-combustion CO<sub>2</sub> capture is one of the most studied technologies for reducing CO<sub>2</sub> emissions in power plants. As a next step for the technology development, large-scale demonstration capture plants have to be implemented. However, two major drawbacks still affect the implementation of post-combustion capture: the high capture cost and the potential emissions of solvents to the atmosphere.

Post-combustion capture process consists in an absorption-regeneration loop as presented on Figure 1. CO<sub>2</sub> from the power plant chemically reacts with an amine solvent at about 40-60°C in the absorber (scrubber column). The benchmark solvent for post-combustion capture is monoethanolamine (MEA). During the absorption, which is an exothermic reaction, the flue gas gets warmer and its water content increases. Consequently, the flue gas containing 90% less CO<sub>2</sub> after the absorption has to be washed with cold water to minimize water and amine losses before being vented to the atmosphere. The CO<sub>2</sub>-loaded solvent flows to the stripper where it is regenerated at a higher temperature (about 120°C for MEA). After condensation of water, the released CO<sub>2</sub> is almost pure and may be valorized (applications in food industry, enhanced oil recovery...) or stored underground. The regenerated solvent flows back to the absorber.

Although different studies about CO<sub>2</sub> capture have been published in the last decade, the dynamic behaviour of capture plants has only been investigated more recently. Ziaii et

al. (2011) developed a rate-based model of the capture process using Aspen Custom Modeler and used it to maximize the power plant profit at different prices of electricity and CO<sub>2</sub>. Lin et al (2011) studied the dynamics of the absorption-regeneration loop in Aspen Plus Dynamics and stated that the control of the process water balance was essential for system long-term stability. Panahi and Skogestad (2011) developed a Unisim model to identify the best control variables for achieving optimal CO<sub>2</sub> removal. Harun et al. (2011) and Lawal et al. (2010) modeled the process using the gPROMS modelling environment. This latter study also evidenced the importance of regulating the absorber water balance to prevent severe operational problems like corrosion due to higher MEA concentration in the solvent. Gaspar and Cormos (2011) developed a rate-based CO<sub>2</sub> capture model in Matlab/Simulink and validated it with experimental results.

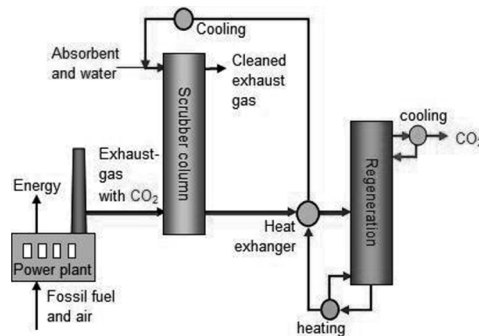


Figure 1: Simplified scheme of the post-combustion CO<sub>2</sub> capture (Bellona, 2012)

Although some of those studies highlighted the importance of controlling the water balance in the process, this was usually done by a water make-up flow, and the absorber washing section was usually neglected excepted in the case of Kvamsdal et al. (2010) who studied CO<sub>2</sub> capture from a NGCC power plant. However, flue gas washing is essential to prevent solvent emissions to the atmosphere. Moreover, a water make-up flow would induce excessive water consumption in large-scale demonstration plants. In existing commercial CO<sub>2</sub> capture plants, the water balance is usually regulated by the relative gas temperatures in/out of the absorber. The objective of the present study is then to propose a dynamic model of the CO<sub>2</sub> capture process including an absorber washing section and to evaluate the regulation of the water balance with no water make-up flow. A control strategy is developed with controller tuning based on the SIMC method. The simulation is implemented in Aspen Plus Dynamics v7.3.

## 2. Model description

Two different approaches may be considered when modelling reactive absorption in columns: equilibrium and rate-based models (Kenig et al., 2001). Equilibrium approach considers each theoretical stage of the columns at a state of thermodynamic and chemical equilibrium, neglecting mass and heat transfer limitations. Rate-based approach is more rigorous since such limitations are considered. However, Abu-Zahra (2009) has shown that both approaches may be applied successfully to the case of CO<sub>2</sub> capture with MEA, with the remark that rate-based models give better predictions for detailed column design. In the present study, both models have been developed for steady-state simulations in Aspen Plus, but dynamic simulations in Aspen Plus Dynamics are only possible with an equilibrium-based model.

### 2.1. Steady-state rate-based model

A steady-state rate-based model has been developed in Aspen Plus to optimize the L/G ratio of the absorber at different flue gas loads. It is adapted from a rate-based model described previously (Léonard and Heyen, 2011). The model has been updated using thermodynamic properties from Aspen Plus 7.3.2 databanks and packing characteristics corresponding to the Esbjerg pilot plant (Faber et al., 2011). The number of stages has been extended to 20 in both absorber and stripper.

### 2.2. Dynamic equilibrium-based model

Since Aspen Plus Dynamics does not allow the use of the rate-based approach, an equilibrium-based model has been used for the dynamic study. In order to get similar column performances compared to the rate-based model, the absorber contains 3 equilibrium stages, and the stripper 9 stages (including 2 stages washing section). The absorber washing section has been modelled by a separate 2-stages column so that its dynamic behaviour may be easily studied. Excess water condensing from the flue gas in the washing section is recycled to a buffer tank part of the amine solvent loop. Coherent pressure profiles have been achieved using design specifications in steady-state mode. Based on this equilibrium model, a pressure-driven model has been developed for dynamic simulations (Figure 2).

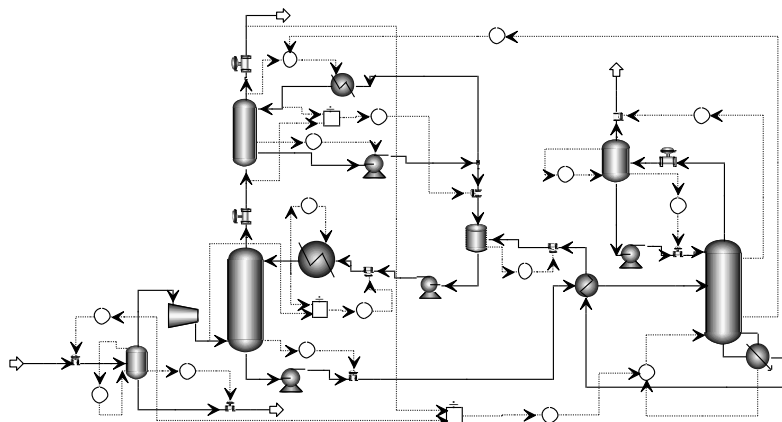


Figure 2: Dynamic model of a pilot capture plant using Aspen Plus Dynamics

13 degrees of freedom (corresponding to valves and heat duties in the process) and 13 constraints have been identified, so that no degree of freedom is left for optimization. The pairing between constraints and degrees of freedom is the following:

- The sump liquid levels of the absorber, the flue gas pre-cooler, the condenser and the solvent buffer tank are controlled by valves;
- The sump liquid level of the washer is controlled by a variable-speed pump;
- The temperatures of the flue gas pre-cooler, the condenser and the solvent flow at the absorber inlet are fixed at 40°C;
- The stripper pressure is fixed at 1.7bar (optimal regeneration pressure identified from the steady-state model);
- Absorber and washer L/G ratios are controlled by varying liquid flow rates;
- The CO<sub>2</sub> capture rate is maintained at 90% by varying the reboiler heat duty;
- The stripper sump level is reflecting the water balance in the process. The regulation is achieved by varying the washing water temperature at the washer entrance.

This latest point is a main difference compared to previous studies where the water balance is regulated by a water make-up stream. In the present paper, the regulation by the washing temperature minimizes the process water consumption, since the make-up water is contained in the flue gas and condensed in the washing section. Controllers are tuned using the SIMC method described by Skogestad (2006).

### 3. Modelling results

The objective of the developed model is to predict the dynamic behaviour of a post-combustion capture pilot plant similar to the Esbjerg pilot plant in Denmark (Faber et al., 2011) and to propose an innovative control strategy for the regulation of the process water balance. The efficiency of this control strategy is evaluated by its ability to reject small disturbances. Capture flexibility is evaluated through different scenarios.

#### 3.1. Disturbance rejection

Process disturbances may be numerous and diversified. To simulate them, some controllers set-points have been manually varied (Table 1). In all cases studied, the process answer was rapid and the disturbance had no major influence on the stability. The capture rate was kept constant at  $90 \pm 1\%$ . Process energy consumption (in GJ/ton CO<sub>2</sub>) stabilized very quickly. Liquid level variations in the columns were kept within a few centimeters. In conclusion, the control strategy at nominal operating point can efficiently reject process disturbances.

Table 1. List of simulated disturbances

Variable	Variation around nominal set-point
Capture rate	$90\% \pm 1\%$
Solvent temperature at absorber entrance	$40^{\circ}\text{C} \pm 3^{\circ}\text{C}$
L/G ratio in the absorber	$0,0045 \pm 0,00009$
L/G ratio in the washer	$0,0045 \pm 0,00009$
Stripper pressure	$1.7\text{bar} \pm 0.1\text{bar}$
Condenser temperature	$40^{\circ}\text{C} \pm 3^{\circ}\text{C}$

#### 3.2. Capture flexibility

In order to ensure maximum flexibility for power plants equipped with CO<sub>2</sub> capture, it is essential to study the dynamic behaviour of the capture process when the electricity demand increases (daily peak hours). Electricity production can temporarily be increased by reducing the CO<sub>2</sub> capture rate, and thus the steam consumption of the solvent regeneration. Two scenarios are studied. In the first one, the capture rate is decreased at constant flue gas load. In the second scenario, the flue gas load is partially vented to the atmosphere before the capture plant.

##### 3.2.1. Capture rate reduction

In this scenario, the energy available at the stripper reboiler is reduced while the flue gas load and the amine solvent mass flow are kept unchanged. Since the electricity demand peak usually doesn't last very long, it is not recommended to totally shut down the capture installation, but rather to reduce its energy consumption. This is simulated by reducing the capture rate set-point, so that the amine solvent needs to be less regenerated and less energy is requested at the stripper reboiler. We stated that decreasing the capture rate set-point from 90% down to 20% could be achieved in less than 5 minutes without major problem. However, stabilization of the capture rate is longer to achieve, depending on the rapidity of the set-point change.

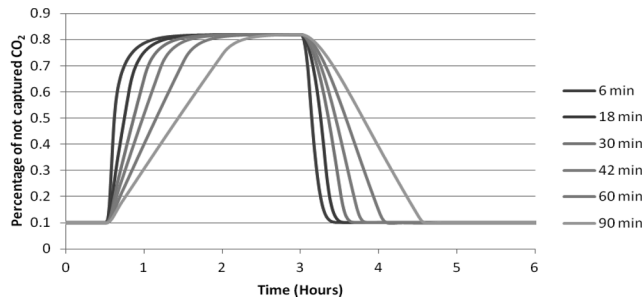


Figure 3: Reduction of the capture rate from 90% (10% of the CO<sub>2</sub> is not captured) to 20% (80% is not captured) when the duration of the set-point change ramp is modified

However, when decreasing the capture rate down to 10%, the stripper liquid level could not be stabilized by varying the washing temperature. In this case, the amine solvent is barely regenerated and absorbs very little CO<sub>2</sub> in the absorber. Since the absorption is an exothermic reaction, the flue gas temperature in the absorber doesn't increase enough, and less water exits the process with the cleaned flue gas, even if the flue gas is not cooled anymore in the washing section. Consequently, water accumulates in the stripper. Since the stripper liquid level rises very slowly (about 1cm/hr), it will only be problematic if the 10%-capture rate regime lasts for several hours.

### 3.2.2. Load reduction

A steady-state rate-based study shows that the optimal L/G ratio in the absorber remains reasonably constant when the flue gas load is varying between 100% and 30% of its nominal value, see Figure 4. We then decided to keep the absorber L/G ratio constant and equal to 0.0045 as the energy consumption varies less at slightly higher L/G ratio.

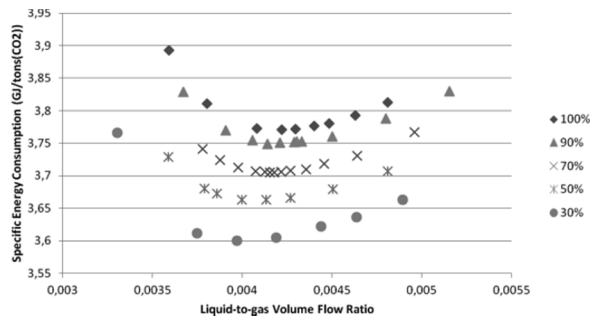


Figure 4: L/G optimal ratio in the absorber doesn't vary much with flue gas load

When reducing the flue gas load down to 20% of its nominal value, the solvent mass flow is then reduced to keep the L/G ratio constant. As a consequence, we observe that column hold-ups decrease and liquid levels increase in all equipments so that level controllers are not able to stabilize the process anymore. The only solution is to adapt the set-point of the liquid level controllers during the load reduction ramp. In this case, it is possible to reduce the flue gas load down to 10% of its nominal value in only 6 minutes. However, if the way back to 100% load is achieved in 6 minutes as well, some process instability is observed because of water accumulation in the condenser. Indeed, due to a too strict control of the capture rate, the stripper sump temperature increases sharply, evaporating more water than what can be recycled from the condenser. This problem can be solved by loosening the capture rate control.

#### 4. Conclusion

As it appears from the study of the capture process dynamics, it is essential to control the process water balance to prevent water accumulation in the columns. Contrarily to previous works where this regulation was assumed by a variable water make-up flow, the amount of water exiting the process may advantageously be controlled by the flue gas temperature in the absorber washing section. This alternative control strategy successfully rejected process disturbances. Two scenarios were studied for reducing the capture process energy consumption during electricity peak hours. Both cases allow an important reduction of the energy consumption within a few minutes. Potential operational problems are identified and solved. Further model developments will include solvent degradation phenomena in order to perform a multi-objective optimisation of the capture process in steady-state mode.

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