Process Control Strategy of Amine-Based Post-Combustion CO₂ Capture Systems

Ana-Maria Cormos*, Madalina Burca, Flavia Ilea, Mircea-Vasile Cristea

Babes – Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos, Postal code: RO-400028, Cluj – Napoca, Romania
cani@chem.ubbcluj.ro

CO_2 removal with alkanolamine solvent is the most advanced technology to be deployed on a large scale; the CO_2 capture pilot plants from worldwide had already demonstrated the feasibility of this technology. The main drawback of the implementation of CO_2 capture unit is the high energy penalty associated with CO_2 absorption process. For power plants equipped with carbon capture, the load-following operation of the power block will also affect the post-combustion CO_2 capture unit. The implementation of a control strategy is necessary for the flexible operation of CO_2 capture process during the periods of fluctuation in the plant loading. The main objective of the control system is to assure the efficiency of the process EP, which means a high CO_2 capture rate CC% with minimum requirements of energy for regeneration of the solvent. The desired values for these operating goals are situated in the range of 80 – 90 % for CC and 3 – 4 MJ/kgCO₂ for EP. Another objective of the control strategy is to maintain a constant molar ratio between inlet CO_2 flow and MEA flow introduced in the absorption process (to assure enough solvent flow to capture at least 80 % of the CO_2 and not wasting it). The molar ratio can be controlled either by solvent flow rate or by solvent concentration, using a ratio controller. EP index is controlled indirectly through the CC parameter, CC is controlled by the reboiler heat duty, molar ratio is controlled by solvent flow rate while temperature and level in the buffer tank are controlled by thermal agent flow rate, respectively fresh MEA flow rate introduced into the buffer tank. The designed control system merges ratio, feedforward and feedback decentralised control. The simulation results showed that the control strategy proposed can handle the fluctuations in the upstream power plant load and the imposed set-point changes, providing flexibility to the operation of the process.

1. Introduction

Although solvent-based CO_2 capture is a mature technology which is applied for various industrial chemical processes, the implementation in power plants to remove CO_2 from flue gas is limited because the operation demands of this system and high energy penalty associated to CO_2 absorption process. Besides, post-combustion CO_2 capture station incorporated in a power plant must cope with various perturbations coming either from the power production unit or from the solvent absorption-regeneration loop.

To minimize these inconveniences, the operation of post-combustion CO_2 capture process must be optimized using a proper control strategy. The aim of the control system is to reduce the disturbances effect caused by process interactions and to maintain the energy performance indexes in the near-optimal range.

Recently, several studies on the CCS process control have been performed. Most of these studies are focused on dynamic modelling and implementing PI/PID control strategies, but there are some works that present studies on more advances technologies such as MPC. Nittaya et al. (2014) presented a mechanistic model of MEA absorption CO_2 capture process with the purpose to conduct a controllability study. Three control decentralized structures were proposed, using conventional PI controllers: a RGA (Relative Gain Array) - design based control strategy and two heuristic control approaches. A similar study was performed by Gaspar et al. (2016) using the same RGA approach to design a control structure for a solvent-based CO_2 capture process. Mechleri et al. (2017) also studied and designed some PID control strategies. The conclusion of the study was that it is worth using a well-tuned control system, even if it is applying a simple and conventional control technology, such as PID, because it keeps the critical parameters in the desired range and avoids auxiliary process equipment costs

(such as the storage tank). Luu et al. (2015) performed a process control analysis based on three control schemes in order to evaluate their performance, proposing a standard PID feedback control scheme, a cascade PID and a model predictive control (MPC) scheme. They concluded that both PID and MPC controllers were able to track the set points and reject the disturbances, but MPC controllers are more efficient regarding the need of obeying constraints. Wu et al. (2018) use a combination of multiple MPCs designed at different operating points to achieve a wide range of flexible operation of a MEA- based CO_2 capture plant. They used a process model developed in gCCS, to which a nonlinearity study was performed and then an MMPC strategy was implemented.

2. Model development

The process flow diagram is presented in Figure 1. It is assumed that the flue gas introduced into absorption process is dry and free of SO_2 and it is considered as a mixture of air and CO_2 with a concentration if 10 – 12 % CO_2. The flue gas flows from the bottom to the top of the absorption column in counter current with the lean solvent. The scrubbed flue gas, with low concentration in CO_2 is released into atmosphere. The rich amine solution loaded with CO_2 is evacuated at the bottom of the absorber and flows to the cross heat exchanger where is preheated before fed to the desorber. For steady-state operating condition, the mass flow of CO_2 captured is about 5,600 kg/h, for a reboiler duty of about 2.1 MW.

The process model is based on the dynamic model proposed by Gaspar and Cormos (2011). The simulation results of this model, in terms of mass and heat balances, were validated against the pilot plant data published in Tobiesen (2017). Moreover, there were introduced some additional models for equipment units as a cross heat exchanger and a buffer tank for storage of the lean solvent recycled from desorber to absorber. Besides, a scale-up of the initial pilot plant model was performed, in similar operation conditions, consisting in 3.89 m height of packing and 0.15 m diameter of the column to 22 m height and 1.5 m diameter for absorber and   11 m height and 1.3 m diameter for desorber (Enaasen Flo, 2015). The dynamic model consists of partial-differential equations describing the gas-liquid system of CO_2 absorption/desorption and others constitutive relations used to compute hydraulic and pysico-chemical properties of the components. In Table 1 are presented these equations, for the packed column as well as the equations used to model the auxiliary process units. The mathematical model was implemented and solved in MATLAB/Simulink software. To achieve process efficiency simultaneously with an energy consumption optimization, a control scheme based on conventional PI technology is proposed. The effectiveness of the control strategy is assessed against the ability to track the set point value and to reject typical disturbances. This study is demanded because the process control is the only way this process can be operated in such a manner to be economically convenient.

To evaluate the performance and the efficiency of the capturing process, two parameters are the most important: the process capture rate as a ratio between the mass of CO_2 captured and the mass of CO_2 introduced in the process with the flue gas, CC % Eq(1) and the energy performance which is the energy consumed to release one kg of CO_2 absorbed in the solvent EP MJ/kgCO_2, Eq(2). The desired values for these parameters are in the range of 80 – 90 % for CC % and 3 – 4 MJ/kgCO_2 for EP. The objective of the control strategy is to maintain CC % and EP to optimal values.
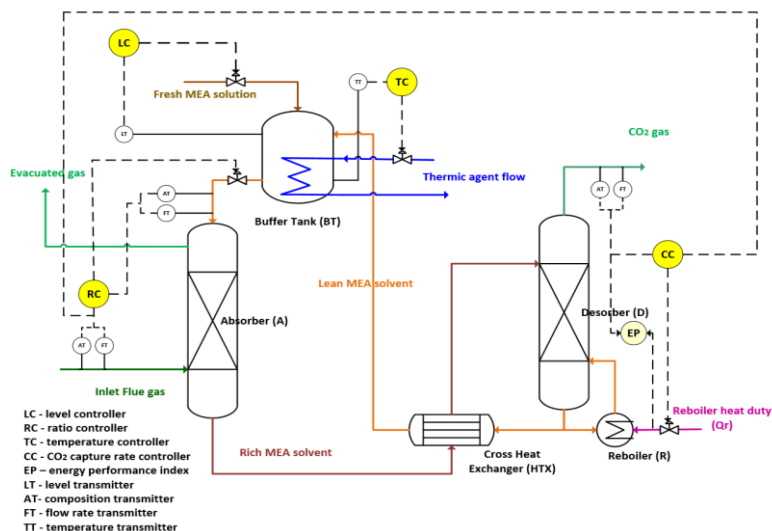

LC - level controller
RC - ratio controller
TC - temperature controller
CC - CO_2 capture rate controller
EP – energy performance index
LT - level transmitter
AT- composition transmitter
FT - flow rate transmitter
TT - temperature transmitter

Figure 1: Process flow diagram with its associated control system

Table 1: Mathematical model balance equations

Absorber/Desorber	
Liquid phase	Gas phase

Total mass balance

$$\frac{\partial F_L}{\partial t} = -v_L \cdot \frac{\partial F_L}{\partial z} \pm \frac{v_L \cdot A \cdot a_e}{\rho_L} \cdot \sum (M_i \cdot N_i) \qquad \frac{\partial F_G}{\partial t} = -v_G \cdot \frac{\partial F_G}{\partial z} \pm \frac{v_G \cdot A \cdot a_e}{\rho_G} \cdot \sum (M_i \cdot N_i)$$

Component mass balance

$$\frac{\partial C_i^L}{\partial t} = -v_L \cdot \frac{\partial C_i^L}{\partial z} \pm a_e \cdot N_i \pm \upsilon_i^R \cdot N_R \qquad \frac{\partial C_i^G}{\partial t} = -v_G \cdot \frac{\partial C_i^G}{\partial z} \pm a_e \cdot N_i$$

Heat balance

$$\frac{\partial T_L}{\partial t} = -v_L \cdot \frac{\partial T_L}{\partial z} - \frac{N_R \cdot \Delta_R H}{\rho_L \cdot c_{pL}} +$$

$$\frac{K_T^i \cdot a_e \cdot (T_G - T_L)}{\rho_L \cdot c_{pL}} - \frac{a_e}{\rho_L \cdot c_{pL}} \cdot \sum (N_i \cdot \Delta H_v^i) \qquad \frac{\partial T_G}{\partial t} = -v_G \cdot \frac{\partial T_G}{\partial z} + \frac{K_T^i \cdot a_e \cdot (T_G - T_L)}{\rho_G \cdot c_{pG}}$$

Cross-heat exchanger	
Heat balance for rich amine solution	Heat balance for lean amine solution

$$\frac{dT_r}{dt} = \frac{F_r}{V_r} \cdot (T_{r\_in} - T_r) + K_T \cdot A_T \cdot \frac{T_l - T_r}{\varphi_r \cdot cp_r \cdot V_r} \qquad \frac{dT_l}{dt} = \frac{F_l}{V_l} \cdot (T_{l\_in} - T_l) + K_T \cdot A_T \cdot \frac{T_l - T_r}{\varphi_l \cdot cp_l \cdot V_l}$$

Buffer tank	
Component mass balance	Heat balance

$$\frac{dC}{dt} = \frac{1}{V} \cdot \Sigma (F \cdot cp \cdot T) - \frac{C}{V} \cdot \frac{dV}{dt} \qquad \begin{aligned} \frac{dT}{dt} &= \frac{1}{V \cdot cp} \cdot \Sigma (F \cdot cp \cdot T) - \frac{T}{V} \cdot \frac{dV}{dt} + \\ &+ K_T \cdot A_T \cdot \frac{T - T_T}{\varphi \cdot cp \cdot V} \end{aligned}$$

Note: G, L- indicate the gas/liquid phase; i represent the chemical species: CO_2, O_2, MEA, H_2O; R represent the chemical reaction of absorption, t,z – indicate the time and space coordinates of the system.

$$CC = \frac{CO_{2-captured}}{CO_{2-intrduced}} \cdot 100[\%] \tag{1}$$

$$EP = \frac{Q_r}{CO_{2-captured}} \left[\frac{MJ}{kgCO_2}\right] \tag{2}$$

Another objective of the control strategy is to maintain a constant molar ratio between the inlet CO_2 flow and MEA flow introduced in the absorption process. The advantage of this goal is to assure enough solvent flow to capture at least 80 % of the CO_2 coming with the flue gas, regardless of fluctuations in the flue gas flow rate or concentration. According to this target, the molar ratio can be controlled either by the solvent flow rate or by solvent concentration, by means of a ratio controller, considering that the ratio will freely vary depending on the flue gas fluctuations. On the other hand, if solvent concentration is chosen as manipulated variable, it should be also considered that the solvent flow rate would vary depending on the perturbations that occur with the incoming combustion gases.

Table 2: Manipulated MV and controlled CV variables

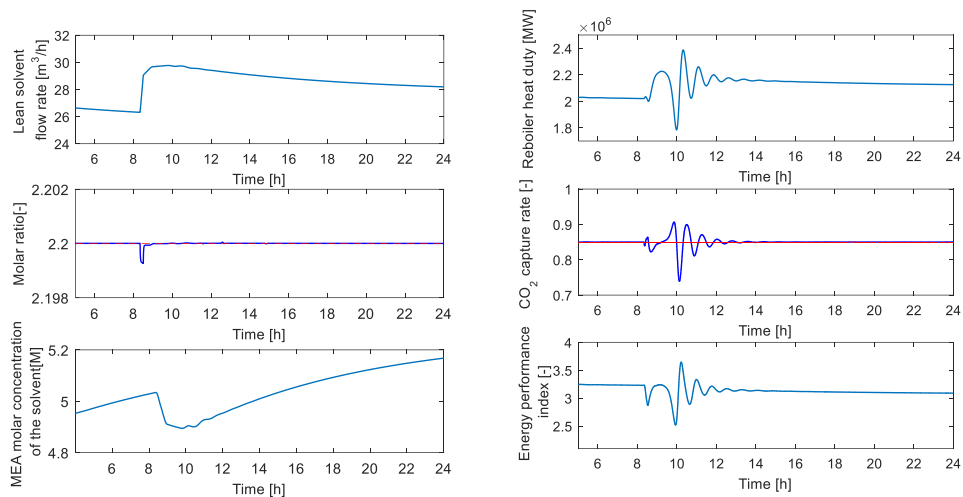|		Variables	Nominal steady-state value
MV	1. F_{L_MEA}	Lean solvent inlet flow rate (m³/h)	25.2
	2. Q_r	Reboiler heat duty (MW)	2.1
	3. F_{F_MEA}	Fresh MEA solvent flow rate (m³/h)	3
	4. F_{TA}	Thermal agent flow rate (m³/h)	35.3
CV	1. RR	Reactants molar ratio (-)	2.17
	2. CC %	CO_2 capture rate (%)	87
	3. L_{BT}	Liquid level in buffer tank (m)	3.94
	4. T_{BT}	Temperature in buffer tank (K)	320

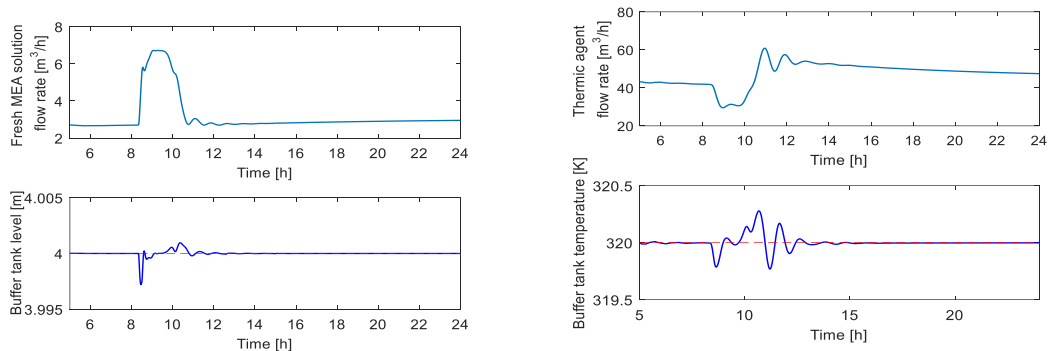Figure 2: (a) Controlled process response (ratio control). (b) Controlled process response (CC % control)

Figure 3: Response of the controlled level and temperature in the buffer tank

As shown the Table 2, the solvent flow rate is selected as manipulated variable for the ratio controller, and MEA concentration is free. Molar ratio between reagents introduced in the column is set so that there is a slight excess of MEA in the column. The control structure is presented in the Figure1.

Responses of the PI control system to a 10 % increase of the flue gas flow rate are presented in Figure 2a – 2b. The ratio controller response is prompt regarding the disturbance rejection, showing small overshoot and short settling time. In Figure 2a it can be observed the response to this perturbation of the solvent flow rate (the manipulated variable), associated to the controlled molar ratio and the MEA concentration variations. The CC% control loop response is characterized by a longer settling time, compared to ratio controller, as it is shown in Figure 2b, revealing associated variations of the reboiler duty and energy performance index. The responses of buffer tank level and temperature control loops are presented in Figure 3. For both of them the overshoot is very small around their set-points, but the manipulated variables changes are large. Also, the settling time is about few hours, as in the case of CC % controller.

In the case of +/-10 % flue gas flow rate disturbance scenario, the responses of the controlled level and temperature are not so regular. Continuing the investigations with the very challenging scenario of periodic disturbances of flue gas flow rate, it may be observed that CC % controller presents larger overshoots, with longer settling time, as it is shown in Figure 4a. Furthermore, the variation of the reboiler heat duty reaches the saturation upper value and the energy performance value shows relatively higher picks. However, it is important to notice that, despite of the large and periodic disturbances, the control brings back to the set point the value of CC %. The mean value of the CC % during the simulated time is about 84.4 % with associated Qr = 2.6 MW and EP = 4.1 MJ/kgCO$_2$ values. The responses of the controlled buffer tank show that the controlled variables are kept very precisely to their set points, with reduced overshoots. This is accomplished with the expense of large variations of the manipulated variables.

Figures 4b – 5 present the responses of the PI controlled process to a periodic +/-10 % inlet CO_2 concentration periodic disturbance scenario, as it is presented in the top of Figure 4b. As in the previous case, the ratio control, the buffer tank level and temperature control, Figure 5, are keeping the controlled values very tight to the set point value, with small overshoots and a relative short settling time. The most challenging was to control the CC % parameter. The response of the controlled process is presented in Figure 4b and shows larger settling time. For this case the mean values of the parameters during the simulated time are the following: CC % = 84.6 %, Qr = 2.33 MW and EP = 3.57 MJ/kgCO_2.
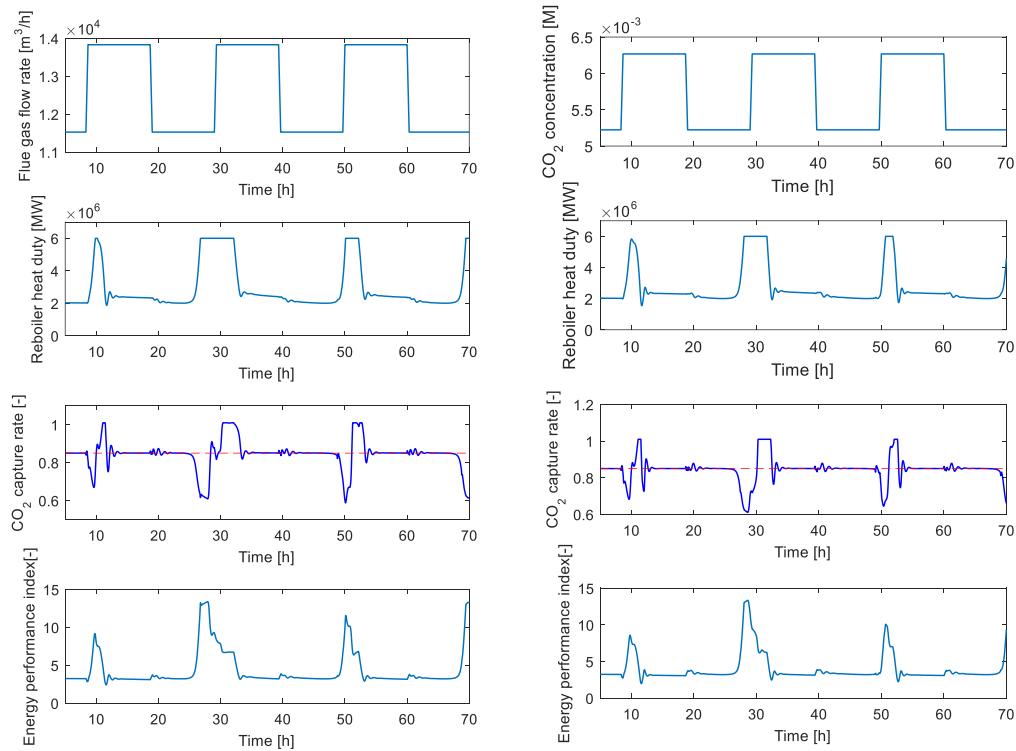

Figure 4: (a) Controlled process (CC % control), case of the flue gas flowrate disturbance. (b) Controlled process response (CC % control), case of the flue gas concentration disturbance
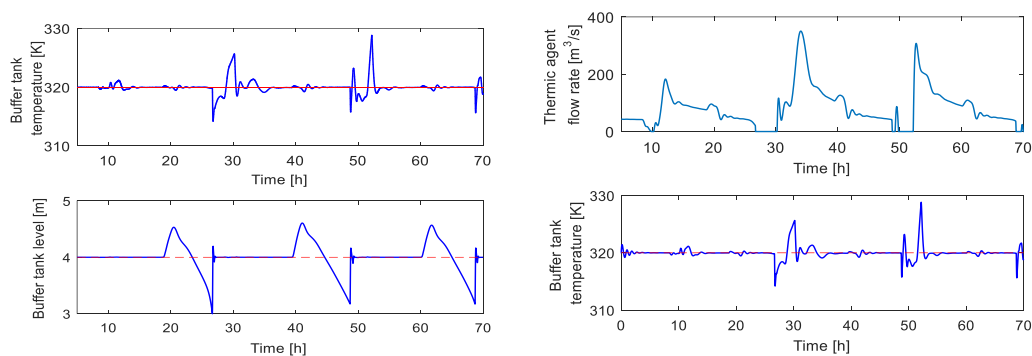

Figure 5: Response of the controlled level and temperature in the buffer tank

3. Conclusions

A rate-based model was developed for post-combustion CO_2 capture process, using MEA aqueous solution as sorbent. Starting from a pilot scale validated model of absorption and desorption columns, a scale-up has been conducted in order to simulate an industrial scale CO_2 capture process. Two additional process units have been

implemented in the model: a buffer tank for the storage of regenerated solvent and a cross heat exchanger for heat recovery. The process units added to the model were essential to simulate the entire absorption-desorption loop and to design an efficient control system for this process.

A decentralized control system based on PI technology has been developed. The main objective of the control system was to assure the efficiency of the process, which means a high CO_2 capture rate CC % with minimum requirements of energy for the regeneration of the solvent. The control of CC % is done by manipulating the reboiler heat requirement. The aim is to maintain the CC % value to an average of 85 %.

The control system performance has been evaluated with respect to both disturbance rejection and set point tracking abilities, in the presence of persistent step and periodic change of disturbances. The considered disturbances consist in the flue gas flow rate and CO_2 concentration changes. The responses of the controlled process variables to these disturbances, show that the proposed, designed and tested control strategy is able to maintain the parameters of the process to the setpoint values and with reduced overshoot, typically less than 10 % for the quickest and less than 20 % for the slowest of the processes. Simulation results have demonstrated that for the periodic flue gas flow disturbance the control system succeeds to keep the mean value of the CC % target variable at 84.4 %, associated to the Qr = 2.6 MW and EP = 4.1 MJ/kgCO$_2$ suitable values. For the case of the periodic flue gas concentration disturbance the proposed control system achieves for the CC % target variable the mean value of 84.6 %, associated to the beneficial results of Qr = 2.33MW and EP = 3.57 MJ/kgCO$_2$. Depending on the controlled variable time response and the type of disturbance scenario the settling time spans from minutes, as it is the case of the flue gas to MEA flow rate ratio or MEA tank inventory control, to a few hours of the CC % control case with its associated EP index.

The main conclusion of the study is that with a decentralised PID control structure and using an appropriate designed control strategy it is possible to maintain the most important parameters of the process, as are the CO_2 capture rate and energy performance index, at desired setpoint values.

Acknowledgements

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