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Control of the CO_2 Capture Using the Absorption and Stripping System for Improved Performance

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The paper presents a new control system configuration for the post combustion CO_2 carbon capture process using amines. The control system structure consists in six control loops and has in its core the cascade control strategy. The proposed cascade control system has the desired carbon capture rate as the master controller target, and the molar ratio between the lean MEA and the influent CO_2 flowrates as the slave controller manipulated setpoint. They have associated the reboiler temperature control in the stripper and the concentration of MEA, temperature and level control in the buffer tank. The buffer tank, accompanied by its control loops, was specifically introduced in the carbon capture plant in order to reduce the interaction between the absorption and stripping units. The decentralized control system was tested for assessing its performance to cope with the typical influent CO_2 flowrate disturbance, considered to act in a periodic scenario. Good disturbance rejection and effective restoration of the nominal operation state were achieved, while the energy performance index value was kept at reduced values. They demonstrate valuable operation flexibility of the controlled CO_2 carbon capture plant.

1. Introduction

The European Strategic Energy Technology Plan (EC, DG Energy, SET-Plan, 2015) aims to accelerate the innovation, development and deployment of cutting edge European low carbon technologies to facilitate the achievement of the 2050 targets. For instance, the EU climate and energy strategy foresees that by 2030 the following targets have to be accomplished: at least 40 % cut in greenhouse gas emissions (from 1990 levels); 32% of energy supplied from renewable energy sources; 35.5 % improvements in energy efficiency. In addition, an ambitious long-term strategy (called European Green Deal) was defined to make EU climate neutral by 2050 - an economy with net-zero greenhouse gas emissions. Thus, it becomes obvious that advanced techniques for capturing and storing of CO_2 – commonly referred as carbon capture and storage (CCS) – are an important part of the solution. There are several alternative technologies for capturing CO_2, for example: gas-liquid absorption, chemical looping, cryogenic methods, membrane separation, biological fixation etc. (IPCC, 2005).

The post-combustion CO_2 capture using amines is one of the most promising technologies under development at the time. However, there is a constant need to increase its efficiency and reduce its associated costs. In achieving this aim, the dependency between the performance of the system and the flexibility of the carbon capture plant needs to be considered. The efficiency of CO_2 capture during transient phases can be improved by prompt action, able to preserve the process performance (Guo et al., 2018). Design and deployment of efficient control strategies reduce the time of disturbed operation and ensures rapid handling of process disturbances induced during the changings of the power plant load.

The CO_2 capture process flowsheet diagram and its associated control system is presented in Figure 1. It includes two packed bed columns (for absorption/desorption processes) and additional equipment units (buffer tanks, heat exchangers). The flue gas, introduced into the absorption process, is considered as a mixture of 10-12 % CO_2. The lean solvent, MEA with 30% mass concentration and a temperature of about 320 K, flows through the absorption column in counter current with the flue gas flow. The scrubbed flue gas, with low CO_2 concentration is released into atmosphere and the rich amine is evacuated from the absorption column and flows to the cross-flow heat exchanger where is preheated before being fed to the stripper. In the desorber the

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reverse reaction takes place and the gas rich in CO_2 is released at the top of the column. At the bottom of the desorber column the solvent is heated in the reboiler and a part of it is evacuated and a part flows to the cross-flow heat exchanger and to the buffer tank thereafter. The lean solvent of MEA is cooled in the buffer tank and is fed to the absorption column, closing the absorption – desorption loop. For steady-state operating conditions the mass of CO_2 captured is about 5,600 kg/h, at the carbon capture rate of 85 % and for a reboiler duty about 2.1 MW.

The present work proposes a new design for the decentralized control system of the post-combustion CO_2 capture plant composed of the absorption-desorption packed bed columns. The control system aims to keep the carbon capture rate at the desired value by implementing a cascade control structure. The goal of the master controller is to control the carbon capture rate while the slave one controls the MEA to CO_2 molar ratio. The cascade control configuration is able to promptly counteract the disturbances acting on the MEA to CO_2 molar influent ratio, reducing the severity and variability they produce on the carbon capture rate, for rapid and effective correction of upsets. The heat duty controls the reboiler temperature. Additionally, temperature, level and concentration of lean MEA entering the absorber are stabilized by dedicated control loops of the buffer tank.

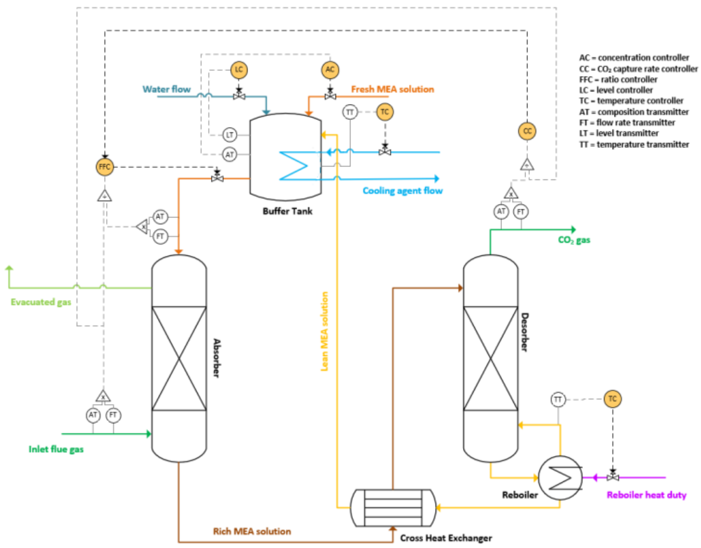

Figure 1: Process diagram and structure of the control system for the post-combustion CO_2 carbon capture plant

2. Mathematical modeling

The performance investigation of the core cascade control strategy for the carbon capture process considered in this work was done using the previously detailed dynamic model developed by authors (Cormos et al., 2015). The model development and implementation, associated to the control system performance investigations were carried out by simulations using Matlab and Simulink software tools (Cristea et al., 2020).

The mathematical model contains partial differential equations (PDE) to describe the total mass, component and energy balance equations of liquid and gas phases for both packed columns (absorber and desorber) and total differential equation in case of additional equipment units: cross-flow heat exchanger and a buffer tank for storage of the lean solvent recycled from desorber to absorber (see Table 1) (Gaspar and Cormos, 2011).

In order to assess the mass and heat transfer processes, the two-film theory was used. The effect of the chemical reaction on the transfer rate is built-in in the transfer equations by the enhancement factor. Moreover, an important part of the developed models is represented by the algebraic equations that describe the mass and heat transfer processes (mass transfer coefficient, effective interfacial area, heat transfer and liquid hold up empirical correlations) and the physical and chemical properties of gas and liquid phase (diffusion coefficients, CO_2 solubility in amine solution, densities, viscosities, specific heat capacities, etc).

The overall process parameters such as chemical species concentration profiles, liquid and gas flow profiles, temperature profile in the liquid and gas phase along the absorption/desorption column and in additional equipment units had been assessed.

Table 1: Mathematical model balance equations

Absorber/Desorber		
Total mass balance	$\frac{\partial F_j}{\partial t} = -v_j \cdot \frac{\partial F_j}{\partial z} \pm \frac{v_j \cdot A \cdot a_e}{\rho_j} \cdot \sum(M_i \cdot N_i)$	(1)
Component mass balance	$\frac{\partial C_i^j}{\partial t} = -v_j \cdot \frac{\partial C_i^j}{\partial z} \pm a_e \cdot N_i \pm \vartheta_i^R \cdot N_R$	(2)
Heat balance	$\frac{\partial T_j}{\partial t} = -v_j \cdot \frac{\partial T_j}{\partial z} - \frac{N_R \cdot \Delta_R H}{\rho_G \cdot c_{pG}} + \frac{K_T^i \cdot a_e \cdot (T_G - T_L)}{\rho_G \cdot c_{pG}} - \frac{a_e}{\rho_G \cdot c_{pG}} \cdot \sum\left(N_i \cdot \Delta H_v^i\right)$	(3)
Cross heat exchanger		
Heat balance	$\frac{dT_{r/l}}{dt} = \frac{F_{r/l}}{V_{r/l}} \cdot \left(T_{r/l\_in} - T_{r/l}\right) \pm K_T \cdot A_T \cdot \frac{T_l - T_r}{V_r \cdot \rho_r \cdot c_{pr}}$	(4)
Buffer tank		
MEA mass balance	$\frac{dC}{dt} = \frac{1}{V} \cdot \sum(F \cdot C) - \frac{C}{V} \cdot \frac{dV}{dt}$	(5)
Heat balance	$\frac{dT}{dt} = \frac{1}{V \cdot c_p} \cdot \sum\left(F \cdot c_p \cdot T\right) - \frac{T}{V} \cdot \frac{dV}{dt} - K_T \cdot A_T \cdot \frac{T - T_T}{V \cdot \rho \cdot c_p}$	(6)

* Note: j - indicate the gas/liquid phase; i represent the chemical species: CO_2, MEA, H_2O; N_R represent the chemical reaction of absorption and ΔHv represent de vaporization enthalpy are included only in liquid phase.

3. Control methodology

Control of the carbon capture amine-based absorption-stripping plant is needed for maintaining the desired operating state that ensures the carbon capture efficiency, with low energy consumptions (at low spent energy) and despite the action of disturbances. Decentralized control with multiple PI or PID control loops (Salvinder et al., 2019,) and Model Predictive Control (Cormos et al., 2015) may be considered as the main control strategies (Nittaya et al., 2014). Strong interaction between the process variables (Luu et al., 2015) and nonlinear behavior (Mechleri et al., 2017), shown when large disturbances are acting, make control a challenging task and affect the linear controllers' performance. Decentralized control still keeps its interest and prevails in the industrial applications due to the straightforward implementation with common instrumentation and to the very well acceptance by the operating staff, while avoiding the need for developing costly models (Cormos et al., 2019).
The design of the multi-loop decentralized control presented in this work considers the disturbance rejection as the main objective of the control system, aiming to keep the carbon capture rate (CC) at the desired setpoint, irrespective of the disturbances action.
CC is computed by the ratio between the mass flowrate of CO_2-outlet exiting the desorber and the mass flowrate of CO_2-inlet introduced the carbon capture plant absorber. Eq(7) describes the CC:

$$CC = \frac{CO_{2-outlet}}{CO_{2-inlet}} \cdot 100\ [\%] \tag{7}$$

The CC was considered a meaningful performance index of the whole carbon capture plant operation under the CO_2 influent changes. Typically, CC values range around 85 %.
The most frequent disturbances of the post combustion carbon capture plant consist in the flow and CO_2 concentration changes of the influent flue gas and, associated to the flow, the concentration and temperature variations of the lean MEA entering the absorber. As a result, the cascade control concept and control system structure were considered to have a good potential for early and efficient rejection of such disturbances. The core of the proposed control system structure, presented in Figure 1, assigns to the cascade master controller the task to maintain the CC at the desired setpoint. The slave control loop is responsible for the maintenance of the molar flowrates ratio of lean MEA and influent CO_2, at the setpoint manipulated by the master controller. According to this control setup the disturbances occurring in the absorber influent CO_2 and lean MEA flowrate or concentration are early undertaken by the slave control loop, diminishing their undesired propagation and disturbing effect on the carbon capture rate main control target.
A buffer tank was added to the couple of the absorber-stripper principal units of the post combustion carbon capture plant for reducing the interaction between these key parts of the plant. The buffer tank is aimed to

temper the temperature, concentration and flowrate upsets that may be caused to the lean MEA entering the absorber due to the changed working conditions in the stripper, smoothening both the absorber and the desorber operation. The control loops designed for the buffer tank include the MEA solvent concentration, temperature and level control.
The decentralized control system is completed by the reboiler temperature control loop, intended to keep the stable and energy efficient operation of the desorption process. The energy performance index EP is assessed as the ratio between the reboiler heat duty, in [MW] and the CO_2-outlet, in [kg CO_2]. The summary of the controlled and manipulated variables of the proposed control system are presented in Table 2.

Table 2: Controlled and manipulated variables of the multiple-loop decentralized control system

Controlled variables	Manipulated variables
Carbon capture rate	Molar ratio of MEA and CO_2 entering the absorber
Molar ratio of MEA and CO_2 entering the absorber	Lean MEA flowrate to the absorber
Temperature in the reboiler	Heat duty to the reboiler
MEA concentration in the buffer tank	Fresh MEA flowrate
Temperature in the buffer tank	Cooling agent flowrate
Level in the buffer tank	Water make-up flowrate

The paring of the controlled and manipulated variables was settled on the basis of phenomenological insight for the process variables dynamic behavior, literature and previous work (Cormos et al., 2019).

4. Results and discussions

The presented multiple-loop decentralized control system was tested for investigating its capability to reject disturbances. As most representative disturbance was considered the flowrate change of the flue gas entering the carbon capture plant, emerged from the upstream power plant operation upsets. A periodic change of the CO_2 influent flowrate was scheduled to act in a scenario consisting in a rapidly rising slope, followed by a constant value of +5% increase and then succeeded by a falling down slope back to the starting level. The shape of the periodic disturbance is presented in Figure 2.

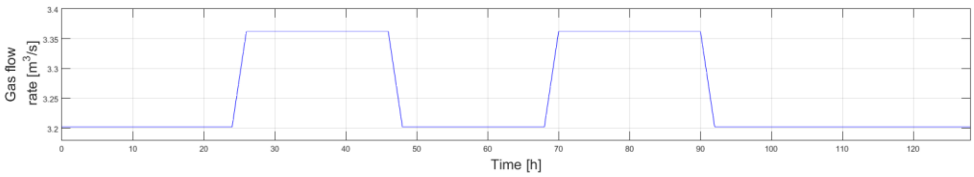

Figure 2: Periodic form of the influent CO_2 flowrate disturbance

Figure 3 shows the results obtained when the periodic disturbance scenario was applied for the controlled variables: carbon capture rate, reboiler temperature in the stripper and molar ratio of MEA and CO_2 entering the absorber. Despite the disturbance action, the carbon capture rate is maintained by the support of the control loops within a reduced interval around the nominal setpoint value of 85 %. The overshoot is limited in a ±5% range around the setpoint. The inner loop of the cascade control system has a prompt response to the disturbance and the molar flowrate ratio of MEA and CO_2 entering the absorber is effectively maintained at the setpoint computed by the carbon capture rate master controller. The reboiler temperature is very tightly controlled to its setpoint, as the overshoot is limited to less than ±0.2 ºK, due to the temperature controller which efficiently manipulates the reboiler heat duty. Figure 4 presents the controlled variables associated to the buffer tank: concentration of MEA, temperature and level. The simulation results presented in Figures 3 and 4 show that the six proposed control loops are able to bring the controlled variables to the specified setpoint values and demonstrate a good rejection capability of the typical CO_2 influent flowrate periodic disturbance. The overshoot is reduced and the settling time is limited. As a consequence, the smooth but flexible operation of the plant is achieved. The energy performance index is maintained at low values and limited overshoot during the disturbance action, as presented in Figure 5.

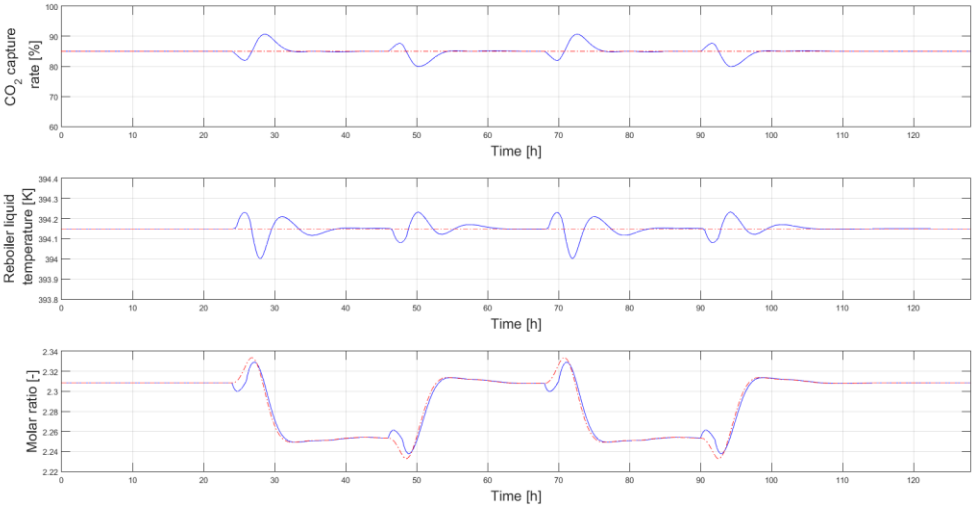

Figure 3: Carbon capture rate, reboiler temperature and molar ratio of MEA and CO_2 controlled variables (red line for the setpoint and blue line for controlled variable)

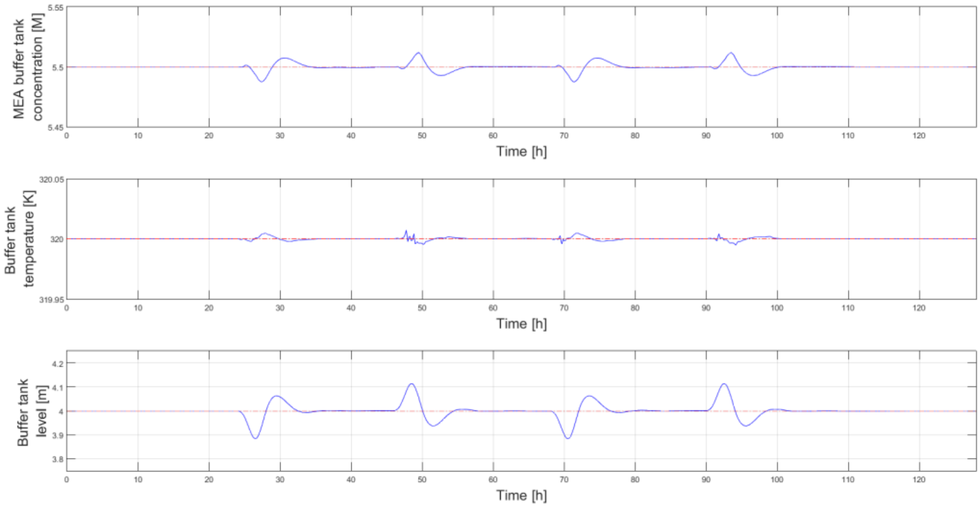

Figure 4: Concentration of MEA, temperature and level controlled variables in the buffer tank (red line for the setpoint and blue line for controlled variable)

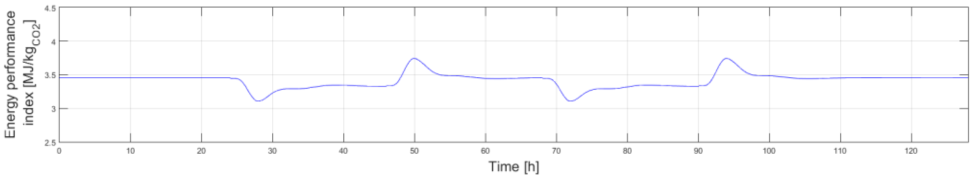

Figure 5: Energy performance variation during the CO_2 influent flowrate periodic disturbance

5. Conclusions

The complex scaled-up model of the absorber-stripper post combustion carbon capture plant, augmented with a buffer tank intended to reduce the interactions between its subunits, was used to investigate the performance of a proposed decentralized control system involving six control loops. The core of the control system for the carbon capture plant has a cascade control structure with the carbon capture rate as main controlled variable and the inner control loop devoted to the control of the molar ratio of lean MEA and influent CO_2 flowrates. These main control loops are assisted by the temperature control in the reboiler and the MEA concentration, temperature and level control in the buffer tank. The performance of the proposed control system was tested for its ability to reject the typical influent CO_2 flowrate periodic disturbance. Results revealed that carbon capture rate main targeted process variable was maintained, with an overshoot limited to less than ±5 %, around the desired setpoint and the setting time was short. By stabilizing the absorber influent MEA concentration and temperature, with the tight control showing less than 1 % overshoot, the efficiency of the cascade control system was enhanced. Their concerted contributions provided flexibility to the carbon capture plant operation and the energy performance index was kept at low values. The proposed control system is proving favourable perspectives for implementation in the post combustion carbon capture plant.

Nomenclature

A – column section, m^2
a_e – effective mass transfer area, m^2/m^3
CC – CO_2 capture rate, %
$CO_{2\text{-inlet}}$ – CO_2 mass flowrate in absorber, kg/s
$CO_{2\text{-outlet}}$ – CO_2 mass flowrate from desorber, kg/s
$C_i^{\,j}$ – concentration of species i in j phase, kmol/m^3
C – concentration of MEA in buffer tank, kmol/m^3
cp_j – specific heat of j phase, kJ/(kmol·K)
F_j – flow of phase j, m^3/s
F – MEA flow, in buffer tank, m^3/s
$\Delta_R H$ – chemical reaction heat, kJ/kmol
$\Delta H_v^{\,i}$ – vaporization enthalpy, kJ/kmol
$K_T^{\,i}$ – thermal transfer coefficient, W/(m^2·K)
M_i – molecular mass of species i, kg/kmol
N_i – transferred flow of species I, kmol/m^2
N_R – chemical reaction of absorption, kmol/m^2
v_j – velocity of phase j, m/s
T_j – temperature of gas/liquid phase, K
$T_{r/l}$ – temperature of rich/lean MEA solution, K
V – liquid volum in buffer tank, m^3
ρ_j – j phase density, kg/m^3

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