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Advanced Control of Post-Combustion Carbon Capture Plant Using PI and Model-Based Controllers

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Despite the energy penalty and solvent regeneration cost, carbon capture using amine-based absorption/stripping systems is one of the most used technologies for CO_2 removal of post-combustion processes, mainly due to its high capture efficiency. This work presents a complex control strategy for a post-combustion carbon capture plant that aims to minimize the effect of disturbances and maintain the desired performance of the CO_2 capture system. It is based on a comprehensive mathematical model for the plant considered to have, in addition to the absorption/stripping columns, a buffer tank and heat exchangers designed to ensure energy efficiency and to determine the flexible, smooth, and robust operation of the plant. The buffer tank is provided with 3 control loops that have the purpose of adjusting the parameters of the absorber inlet solvent solution, such as downstream disturbances that are, to a less extent, recirculated back into the system from the desorber. Using a model predictive control algorithm, an additional control system was designed with the aim to maintain the carbon capture rate of the plant at the setpoint value of 85 % and to keep the reboiler liquid temperature at 395 K setpoint. The control performance results are shown for the hybrid control approach that includes the MPC controller. Results show that the control approach can simultaneously control the targeted variables while efficiently coping with the intrinsic and complex input-output interactions. It is able to maintain better the controlled variables at the desired setpoint values, despite the typical flowrate and concentration disturbances of the CO_2 influent flue gas flow. This is achieved with reduced offset and minimal peak deviations from the setpoints. The mean absolute error values of the controllers are maintained below 7 %, and the carbon capture rate is maintained above 78 % at all times. The energy performance index is maintained at values below 3.5 MJ/kgCO_2.

1. Introduction

The growing threat of global warming and its resultant greenhouse effect has emerged as a pressing concern recently, given its drastic impact on the climate (Khallaghi et al., 2020). To diminish the escalation of average global temperatures, the deployment of carbon capture, storage, and utilization technologies on a global scale is essential (Wang et al., 2018). Researchers are continuously exploring novel and improved Carbon Dioxide (CO_2) capture methods that not only lessen the release of CO_2 into the atmosphere but also do so with minimal environmental consequences and energy waste. However, the energy sector and its mounting demand for power pose a major challenge to these efforts (Cristiu et al., 2022).

Post-combustion carbon capture reduces emissions from fossil fuel-based power plants using mainly monoethanolamine (MEA) as a solvent due to its proven effectiveness. Absorption/stripping systems offer high capture efficiency but still have challenges, such as high solvent regeneration costs and energy penalties (Madeddu et al., 2018). Control strategies for carbon capture plants are essential to optimize the carbon capture rate (CC) and energy performance index, with two main possible approaches: decentralized and centralized control. Model Predictive Control (MPC) algorithms can predict system behavior and optimize carbon capture efficiency while minimizing energy consumption (He et al., 2016). Decentralized control may show benefits when compared to entirely centralized control, being well accepted by operators. It distributes control across multiple controllers, each of which is responsible for a specific part or component of the whole plant (Mechleri et al., 2017).

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The proposed control system in this work incorporates decentralized control and merges it with the MPC control approach. The final goal is to maintain the carbon capture rate at the desired value and to reduce energy consumption. The hybrid system retains the structure of a decentralized control system and enhances it with the addition of an MPC controller. This approach combines the advantages of both control strategies and can provide a more effective and efficient way of controlling the carbon capture process. The decentralized control can offer localized control strategies tailored to specific subunits of the system. At the same time, the MPC controller improves the overall performance of the process by predicting the future behavior of the system and determining the optimal control actions to be taken at each time step (Salvinder et al., 2019). This combined control system can lead to the smooth and stable operation of the carbon capture of the plant, improved energy efficiency, and reduced operational costs (Wu et al., 2020).

2. Process design, main assumptions, and mathematical model

The carbon capture plant considered in this study comprises four subunits: an absorber, a desorber, a buffer tank, and a cross-heat exchanger. The cross-heat exchanger is employed to partially recover the energy used during the desorption process by facilitating heat exchange between the hot lean amine stream and the cold rich amine stream, as the latter requires preheating prior to entering the desorber. The buffer tank operates as a storage unit, serving to temporarily accumulate and stabilize fluctuations in flows and concentrations of components within the system. It is utilized to store the lean amine solution that is fed to the absorber, with the overarching aim of mitigating the magnitude of disturbances that could potentially be recycled back to the absorber from the downstream desorber unit, averting destabilization of the entire plant. The buffer tank includes an inner coil for further cooling of the amine solution. Adjustment of the concentration of the recycled stream is achieved by introducing a fresh amine solution stream into the buffer tank, while fresh water is also added to replenish the water inventory and maintain the desired buffer tank level. The absorber and desorber are packed bed columns that use structured packing. The process flow is presented in Figure 1.

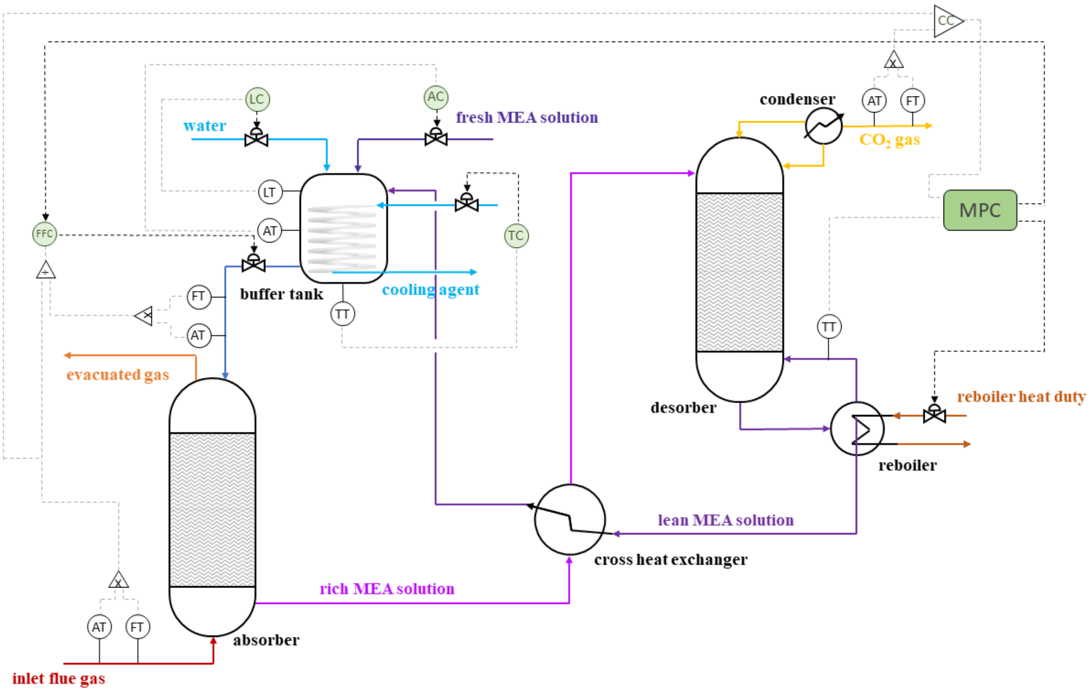

Figure 1: Process flow diagram and control structure (AC = concentration controller, LC = level controller, TC = temperature controller, AT = composition transmitter, FT = flow rate transmitter, LT = level transmitter, TT = temperature transmitter, MPC = model predictive controller)

This study is based on a previously developed mathematical model that describes all equipment units of the process flow (Gaspar et al., 2011). This model was validated against experimental data from pilot plants and scaled up to the industrial level. The control strategy proposed for the process is based on the current requirements of carbon capture plants, taking into consideration the acceptance and ease of operation for the staff. The main design assumptions are presented in Table 1.

Table 1: Equipment units design assumptions

Parameter	Value
Absorber	
Column diameter [m]	1.5
Packing	Mellapack 250Y
Packing height [m]	22
Temperature [K]	320
Pressure [bar]	1.05
Desorber	
Column diameter [m]	1.3
Packing	Mellapack 250Y
Packing height [m]	11
Temperature [K]	380
Pressure [bar]	1.05
Reboiler heat duty [MW]	2.1
Cross heat exchanger	
Shell diameter [m]	0.3
Tube dimensions [mm]	25 x 2
Length [m]	2
Buffer tank	
Diameter [m]	3.2
Height [m]	6

Each equipment unit considered in this work is described by the comprehensive mathematical model, as presented in Table 2.

Table 2: Mathematical model (Ilea et al.,2021)

Absorber/Desorber		
Total mass balance	$\frac{\partial F_j}{\partial t} = -v_j \cdot \frac{\partial F_j}{\partial z} \pm \frac{v_j \cdot S \cdot a_e}{\rho_j} \cdot \sum (M_i \cdot N_i)$	(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	$\frac{\partial T_j}{\partial t} = -v_j \cdot \frac{\partial T_j}{\partial z} - \frac{N_R \cdot \Delta_R H}{\rho_j \cdot c_{pj}} + \frac{K_T^i \cdot a_e \cdot (T_g - T_l)}{\rho_j \cdot c_{pj}} - \frac{a_e}{\rho_j \cdot c_{pj}} \cdot \sum (N_i \cdot \Delta H_v^i)$	(3)
Buffer tank		
Component mass balance (MEA)	$\frac{dC_{MEA}}{dt} = \frac{1}{V} \cdot \sum (F_l \cdot C_{MEA}) - \frac{C_{MEA}}{V} \cdot \frac{dV}{dt}$	(4)
Heat Balance	$\frac{dT}{dt} = \frac{1}{V \cdot c_p} \cdot \sum (F_l \cdot c_p \cdot T) - \frac{T}{V} \cdot \frac{dV}{dt} - K_T \cdot A_T \cdot \frac{T - T_{ag}}{V \cdot \rho \cdot c_p}$	(5)
Cross heat exchanger		
Heat balance	$\frac{dT_{r/l}}{dt} = \frac{F_{r/l}}{V_{r/l}} \cdot (T_{r\_in/l\_in} - T_{r/l}) \pm K_T \cdot A_T \cdot \frac{T_l - T_r}{V_r \cdot \rho_r \cdot c_{pr}}$	(6)

Note: r/l = rich/lean amine stream, L= liquid phase, j = gas/liquid phase, i = component (MEA, CO_2, H_2O), ag = thermal agent

The mathematical model employed in this study describes not only the conservation of mass and energy, but also includes equations that capture the rates of chemical reactions occurring within the various equipment units, as well as the transport phenomena, including heat and mass transfer. The balance equations, along with the reaction rate equations, are integrated to form a system of coupled differential equations, which are then solved numerically using specific computational techniques. The solution of these equations provides valuable insights into the dynamic behavior of the system, enabling the prediction of the temporal evolution of crucial process variables. The dynamic model was used as internal component of the MPC controller.

Apart from the aforementioned equations, the mathematical model used in this study includes equations that describe the thermodynamic properties of the species, such as specific heat coefficients and vaporization enthalpy, that are included in the heat balance. The chemical absorption process is described by the complex zwitterion mechanism and is included in the chemical reaction variation parameter, N_R.

3. Design of the control strategy

The control strategy proposed in this study assumes a hybrid approach, combining elements of both decentralized and centralized control. It is centered around a Model Predictive Control (MPC) controller, which is in charge of controlling the carbon capture rate and the reboiler liquid temperature. Reaching the targeted setpoint values of the MPC controller leads to ensuring the expected system performance and energy efficiency. Additionally, the control strategy incorporates a comprehensive approach for managing the buffer tank variables, comprising three distinct control loops for regulating the concentration of monoethanolamine (MEA) in the buffer tank, maintaining the buffer tank level, and controlling the buffer tank temperature. This extensive control strategy is designed to uphold the efficiency of the carbon capture process, maintaining its smooth operation. These control loops can be identified in Figure 1. Table 3 presents the controlled and manipulated variables of the system.

Table 3: Controlled and manipulated variables

Controlled variable	**Controller**	**Manipulated variable**
Carbon capture rate	MPC	Inlet liquid flow to the absorber
Reboiler liquid temperature	MPC	Influent steam flowrate
MEA concentration	PI	Fresh MEA flowrate
Buffer tank level	PI	Water flowrate
Influent liquid temperature	PI	Cooling agent flowrate

The Proportional Integral (PI) controllers considered for the buffer tank control loops are tuned based on the step response methodology, followed by fine-tuning using an iterative "trial and error" process. This involves adjusting the controller parameters based on observations of the controlled variables response, such as to optimize the control performance (overshoot, response time) of the buffer tank control loops. The tuning process involved the analysis of the plant behavior under various operating conditions and making adjustments to the controller settings to achieve the desired control objectives for MEA concentration, buffer tank level, and buffer tank temperature. The development of the MPC controller involves solving a set of intrinsic optimization problems to determine the optimal control actions that will drive the system towards the desired setpoint values for the carbon capture rate and reboiler liquid temperature variables. The controller uses the comprehensive dataset and the mathematical model of the system to predict the plant behavior over the prediction horizon and optimizes the control actions to achieve the desired objectives. The MPC controller is designed to operate in real-time, continuously updating its predictions and control actions based on the current state of the system, to ensure optimal performance and energy-efficient operation. The MPC controller is designed with two inputs, which are the carbon capture rate and reboiler liquid temperature, and two outputs, which are the manipulated variables used for controlling the system. The prediction horizon, which determines the length of time over which future predictions are made, is set to 10 steps, while the control horizon, which determines the length of time over which control actions are applied, is set to 2 steps, with the sampling time being 180 s.

4. Results and discussion

The process was implemented and simulated using Matlab/Simulink software, incorporating the proposed control design. The results were assessed for revealing the control system performance to achieve disturbance rejection and to keep energy efficiency. This analysis was performed under the scenario of the disturbance in the influent flue gas flowrate (15 % increase/decrease), shown in Figure 2. This scenario mimics the change in energy demand of the power plant providing the influent flue gas.

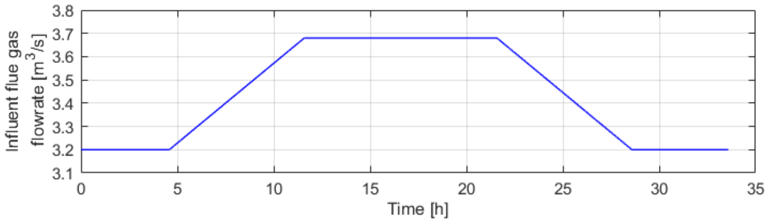

Figure 2: Influent flue gas flowrate disturbance scenario

According to the analysis of the obtained results, the implementation of the MPC controller yielded favorable outcomes in terms of disturbance rejection and setpoint following ability. Compared to the decentralized control strategy, the MPC technique facilitated quicker return to the setpoint value while maintaining low overshoot. These findings suggest that the hybrid MPC – PI control design is a promising alternative to the decentralized control approach that only uses multiple PI control loops. The results are presented in Figures 3 and 4.

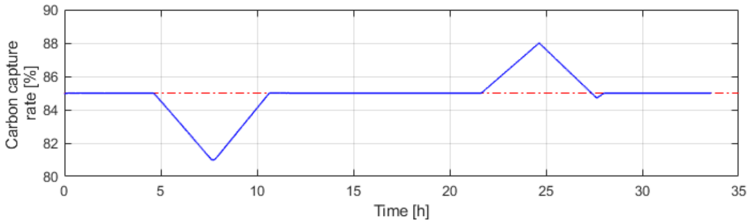

Figure 3: Carbon capture rate control performance

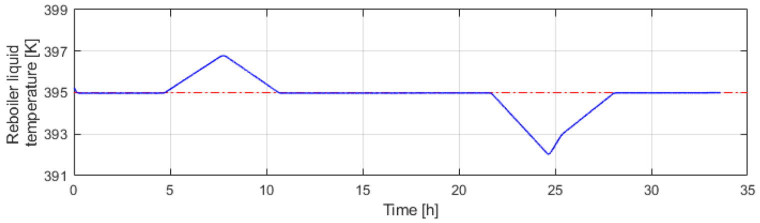

Figure 4: Reboiler liquid temperature control performance

The *behavior* of the plant with the proposed and implemented control system is presented in Figures 3 and 4, for the main carbon capture rate and reboiler liquid temperature controlled variables. Specifically, the red dotted line was utilized to denote the setpoint value, while the blue line was employed to depict the response of the plant variables. The energy performance index in kept at values below 4 MJ/kgCO$_2$ at all times. Its values are changing from 3.1 MJ/kgCO$_2$ to 2.9 MJ/kgCO$_2$, for the considered variation in the flue gas flow. This demonstrates that the combination of a well-maintained carbon capture rate and controlling the liquid temperature value can effectively decrease energy consumption.

The response of the hybrid control system to changes in setpoint values was found to be satisfactory, as shown in Figure 5.

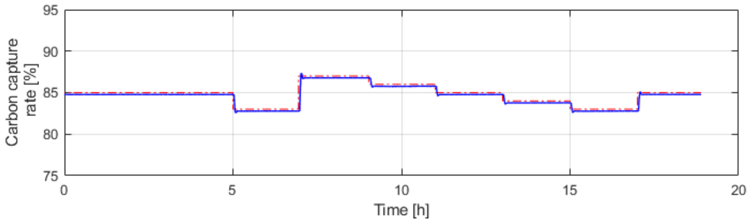

Figure 5: Carbon capture rate setpoint value change scenario

The results indicate that the proposed control system is efficient, providing smooth and flexible operation of the carbon capture plant.

5. Conclusions

The study proposed a hybrid control strategy for controlling the carbon capture rate and reboiler liquid temperature main carbon capture variables, as well as for managing the buffer tank aimed to assist the absorber-desorber units. The control strategy incorporated both model predictive control and proportional-integral controllers. They were fine-tuned for achieving the desired plant performance. The simulation results showed that the implementation of the MPC controller facilitated quicker return to the setpoint value, while maintaining a low overshoot (under 7 %), when they are compared to the decentralized control strategy. The combination of the targeted carbon capture rate and the liquid temperature control resulted in a decrease in energy consumption, as evidenced by the energy performance index being kept below 4 MJ/kgCO_2 at all times. The control system was also found to be effective in responding to changes in setpoint values, enabling smooth and flexible operation of the system. These findings demonstrate that the hybrid MPC-PI control design is a promising control approach alternative for achieving high performance of the carbon capture processes using on the absorption-stripping technology.

Nomenclature

a_e – effective mass transfer area, m^2/m^3
A_T – thermal transfer area, m^2
C – molar concentration, $kmol/m^3$
c_p – specific heat, kJ/(kg·K)
F – volumetric flow, m^3/s
$\Delta_r H$ – chemical reaction enthalpy, kJ/kmol
ΔH_v – vaporization enthalpy, kJ/kmol
K_T – heat transfer coefficient, W/m^2
M – molar mass, kg/kmol
N – molar flow, kmol/(m^2·s)
N_R – chemical reaction variartion, kmol/(m^3·s)
t – time, s
T – temperature, K
v - velocity, m/s
V – volume, m^3
z – length unit, m
ν – stoichiometric coefficient, -

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