

Article

Hybrid Advanced Control Strategy for Post-Combustion Carbon Capture Plant by Integrating PI and Model-Based Approaches

Flavia-Maria Ilea, Ana-Maria Cormos, Vasile Mircea Cristea * and Calin-Cristian Cormos * 

Faculty of Chemistry and Chemical Engineering, Babes-Bolyai University, 400028 Cluj-Napoca, Romania; flavia.ilea@ubbcluj.ro (F.-M.I.); ana.cormos@ubbcluj.ro (A.-M.C.)

* Correspondence: mircea.cristea@ubbcluj.ro (V.M.C.); calin.cormos@ubbcluj.ro (C.-C.C.)

Abstract: Even though the energy penalties and solvent regeneration costs associated with amine-based absorption/stripping systems are important challenges, this technology remains highly recommended for post-combustion decarbonization systems given its proven capture efficacy and technical maturity. This study introduces a novel centralized and decentralized hybrid control strategy for the post-combustion carbon capture plant, aimed at mitigating main disturbances and sustaining high system performance. The strategy is rooted in a comprehensive mathematical model encompassing absorption and desorption columns, heat exchangers and a buffer tank, ensuring smooth operation and energy efficiency. The buffer tank is equipped with three control loops to finely regulate absorber inlet solvent solution parameters, preventing disturbance recirculation from the desorber. Additionally, a model-based controller, utilizing the model predictive control (MPC) algorithm, maintains a carbon capture yield of 90% and stabilizes the reboiler liquid temperature at 394.5 K by manipulating the influent flue gas to the lean solvent flowrates ratio and the heat duty of the reboiler. The hybrid MPC approach reveals efficiency in simultaneously managing targeted variables and handling complex input–output interactions. It consistently maintains the controlled variables at desired setpoints despite CO₂ flue gas flow disturbances, achieving reduced settling time and low overshoot results. The hybrid control strategy, benefitting from the constraint handling ability of MPC, succeeds in keeping the carbon capture yield above the preset minimum value of 86% at all times, while the energy performance index remains below the favorable value of 3.1 MJ/kgCO₂.

Keywords: amine-based absorption; carbon capture; model predictive control; PI control



Citation: Ilea, F.-M.; Cormos, A.-M.; Cristea, V.M.; Cormos, C.-C. Hybrid Advanced Control Strategy for Post-Combustion Carbon Capture Plant by Integrating PI and Model-Based Approaches. *Energies* **2024**, *17*, 2886. <https://doi.org/10.3390/en17122886>

Academic Editor: Fernando Rubiera González

Received: 30 April 2024

Revised: 28 May 2024

Accepted: 8 June 2024

Published: 12 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The greenhouse effect that causes the increase in Earth's average surface temperature is one of the major concerns the planet is facing nowadays [1]. This takes place mainly due to anthropogenic activities (i.e., deforestation, using fossil fuels, and industrial processes), with the phenomenon having far-reaching consequences for the environment. The rise in greenhouse gas emissions encloses heat in the Earth's atmosphere, causing frequent and harsh heatwaves, melting glaciers, rising sea levels, disruptions in weather patterns, and threats to biodiversity [2]. Urgent action is required at both individual and global levels to mitigate the causes of global warming, transition to renewable energy sources, and cope with its inevitable effects to ensure a sustainable future [3]. Scientists are consistently investigating innovative and enhanced techniques for capturing carbon dioxide (CO₂), aiming not only to reduce its emission into the atmosphere but also to achieve this goal while minimizing environmental impacts and energy inefficiencies. Nevertheless, the energetic sector, with its increasing need for electricity, presents a significant provocation to these endeavors [4].

Post-combustion carbon capture technology, primarily employing monoethanolamine (MEA) as a solvent, effectively minimizes CO₂ emissions from fossil fuel-based power plants [5]. Despite its proven efficacy, absorption-stripping systems encounter challenges

such as the steep increase in solvent regeneration costs and energy penalties [6]. Effective control strategies are vital for optimizing carbon capture yield and energy efficiency, offering two principal control strategies: centralized and decentralized control. The centralized model predictive control (MPC) algorithm excels in predicting system behavior and supporting the optimization of CO₂ absorption yield and, at the same time, reducing the energy consumption to a minimum [7]. Decentralized control, highly accepted by operators, may yield advantages in association to the entirely centralized control by distributing control across multiple controllers, each overseeing specific units or variables of the entire plant [8]. Combined, the hybrid centralized and decentralized control may bring benefits by taking advantage of merging their control approaches [9].

The literature emphasizes carbon capture and energy efficiency as primary controlled target variables in carbon capture plants [10]. However, other variables have also been recognized as useful candidates for control, such as the flow rate of lean solvent, column inventory and temperature, as well as water replenishment and reboiler temperature [11]. Authors have also suggested other controlled variables such as the concentration of monoethanolamine (MEA) and predetermined desorber tray temperature, while considering different disturbances, i.e., inlet flue gas flow rate and carbon dioxide concentration [12]. Manipulated variables commonly reported include recycled lean solvent flow rate, reboiler heat duty (steam flow rate), rich solvent flow rate, makeup water flow rate, and cooler duty [13].

Two different control system approaches have been recognized to have good application potential, namely multi-loop decentralized control utilizing proportional–integral or proportional–integral–derivative controllers on the one hand, and centralized multivariable MPC (model predictive control) on the other hand. Additionally, ratio and cascade control strategies have been explored, along with dynamically switching between control strategies [14].

Proportional–integral (PI) controllers are widely used in various control systems due to their simplicity and effectiveness in regulating processes [15]. One of the primary advantages of PI controllers is their ability to quickly respond to changes in the controlled system, as they appropriately combine both proportional and integral actions [16]. The proportional component allows for immediate corrective action, ensuring a rapid response to disturbances [17]. Meanwhile, the integral component helps the elimination of steady-state errors by constantly integrating the error signal over time. Additionally, PI controllers are relatively easy to implement and tune, compared to more complex control algorithms, making them suitable for a wide range of applications. However, PI controllers may struggle with nonlinear systems or processes with significant time delays as they lack the ability to straightforwardly adapt to changing dynamics beyond their preset parameters [18]. Tuning PI controllers can also be challenging, requiring the careful adjustment of proportional and integral gains to achieve optimal performance without causing instability or oscillations in the system. Overall, while PI controllers offer simplicity and effectiveness in most of the control scenarios, their limitations in handling complex dynamics and tuning requirements should be considered when selecting control strategies for specific applications [19].

Model predictive control (MPC) is a complex strategy which offers several advantages for efficiently operating complex industrial processes. One significant advantage is its ability to handle difficult-to-control, multivariable systems having to cope with different types of constraints [20]. MPC uses a time-dependent mathematical model to determine the future behavior of the system and computes the best control actions over a specified prediction horizon, also considering the operating constraints [21]. This predictive capability enables MPC to account for process dynamics, disturbances, and constraints in real time, resulting in improved control efficiency and stability in contrast to traditional control methods. Additionally, MPC provides flexibility in handling various objectives, such as enhancing efficiency, reducing energy consumption, or optimizing product quality, by adjusting the cost function and its associated constraints [22]. However, MPC also comes with some difficulties. It requires a detailed and accurate model of the system, which can

be challenging and time-consuming to develop, especially for complex processes with nonlinear dynamics [23]. Moreover, the computational complexity of solving optimization problems in real time can be demanding, requiring powerful hardware and efficient algorithms. Despite these challenges, the benefits of MPC, including enhanced performance, robustness, and flexibility, make it a valuable tool for advanced control applications at industrial scale plants [24].

Given the aforementioned premises, it can be stated that both MPC and PI controllers possess their own sets of advantages and their combined use for the carbon capture plant control is promising. While the model predictive control algorithm forecasts system behavior, improves CO₂ capture yield and reduces energy consumption, PI control, as a form of decentralized control, can enhance stability, flexibility and operators' acceptance. It disperses control across multiple controllers, each assigned to control specific variables of the system, and assists the achievement of the MPC centralized controller tasks [25].

The proposed control system in this study integrates both a 4×4 decentralized control scheme and an MPC controller with the ultimate objective of keeping the CO₂ capture yield at the preset setpoint value while simultaneously minimizing the energy penalty. The hybrid control strategy design merges the framework of a decentralized control strategy with the integration of the MPC controller. The strengths of the control systems are joined together and can offer high control performance and cost-effective solutions for regulating the carbon capture process. This combined control system results in improved system stability, enhanced energy efficiency, and reduced operational costs.

2. Materials and Methods

The CO₂ capture facility examined in this study consists of four distinct sub-systems: an absorber, a cross-heat exchanger, a stripper, and a buffer tank. The influent flue gas flow is considered to be an air–CO₂ mixture. The cross-heat exchanger is important in reusing energy from the stripper by enabling energy transfer between the cold rich amine stream and the hot lean amine stream [26].

The buffer tank is a retention tank, accumulating and stabilizing fluctuations in the flow rates, temperature and concentrations of the carbon capture process components [27]. Primarily, it stores the solvent solution directed to the absorber, with the purpose of reducing fluctuations that might otherwise be recirculated from the downstream desorber to the absorber, thereby preventing disruptions within the entire system. Additionally, this unit is equipped with an internal cooling coil designed to stabilize the temperature of the solvent solution before it enters the absorption column.

The molarity of the recirculated amine flow is adjusted by adding a fresh mono-ethanolamine stream to the storage unit, whereas fresh water is introduced to reload the spent water and maintain the level at constant value. Both the absorption and the desorption columns employ structured packing as packed bed columns. The process flow and its advanced hybrid control system are illustrated in Figure 1.

2.1. Mathematical Model and Plant Design

To scale the carbon capture process units presented in Figure 1 to an industrial level, a pre-existing and verified mathematical model was utilized. The principal design assumptions are outlined in Table 1.

The mathematical model utilized in this study for describing the CO₂ absorption–desorption process was constructed based on a detailed time-dependent model developed by the authors in previous works [28]. The CO₂ absorption–stripping process in both absorption- and desorption-packed bed columns is governed by the energy and mass balance equations outlined in Table 2 [29].

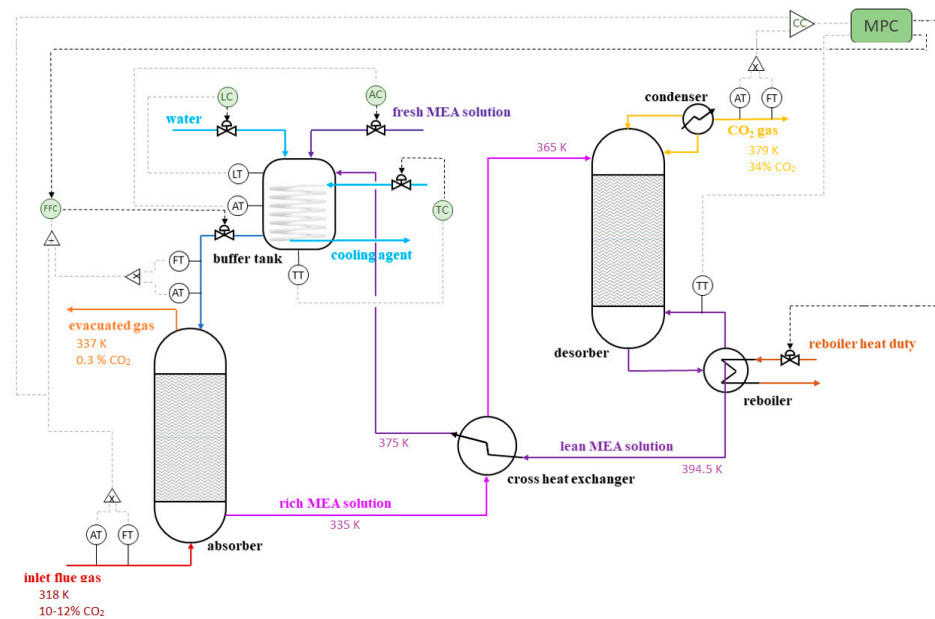


Figure 1. Control strategy design and process flow diagram (TT = temperature transmitter, FT = flow rate transmitter, AT = concentration transmitter, LT = level transmitter, AC = concentration controller, TC = temperature controller, LC = level controller, FFC = ratio controller, CC = carbon capture rate, MPC = model predictive controller).

Table 1. Assumptions for the design of the equipment units.

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

Data provided by Versteeg et al. was employed to adopt the kinetic approach for the reversible chemical interaction taking place with carbon dioxide and monoethanolamine in the absorption–desorption columns. [30]. The mass transfer phenomenon was characterized using the two-film theory, for which the interfacial area, effective mass transfer area, and mass transfer coefficients were determined using correlations reviewed by Rocha et al. [31,32].

Solubility, densities, viscosities, diffusion coefficients, vaporization heats, specific heat capacities and other chemical and physical properties of the MEA-CO₂ aqueous mixture

were calculated based on data from the literature, as they are highly influenced by the concentration of monoethanolamine and process temperature [33].

Table 2. Mathematical model for each equipment unit.

Absorber/Desorber	
Total mass balance	$\frac{\partial F_j}{\partial t} = -v_j \cdot \frac{\partial F_j}{\partial z} \pm \frac{v_j \cdot A \cdot a_e}{\rho_j} \cdot \sum (M_i \cdot N_i)$
Partial mass balance (components)	$\frac{\partial C_i^j}{\partial t} = -v_j \cdot \frac{\partial C_i^j}{\partial z} \pm a_e \cdot N_i \pm \theta_i^R \cdot N_R$
Heat balance	$\frac{\partial T_j}{\partial t} = -v_j \cdot \frac{\partial T_j}{\partial z} - \frac{N_R \cdot \Delta_R H}{\rho_G \cdot c_{pG}} + \frac{K'_T \cdot a_e \cdot (T_G - T_L)}{\rho_G \cdot c_{pG}} - \frac{a_e}{\rho_G \cdot c_{pG}} \cdot \sum (N_i \cdot \Delta H_v^i)$
Buffer tank	
Heat Balance	$\frac{dT}{dt} = \frac{1}{V \cdot c_p} \cdot \sum (F_L \cdot c_p \cdot T) - \frac{T}{V} \cdot \frac{dV}{dt} - K_T \cdot A_T \cdot \frac{T - T_{ag}}{V \cdot \rho \cdot c_p}$
Component mass balance (MEA)	$\frac{dC_{MEA}}{dt} = \frac{1}{V} \cdot \sum (F_L \cdot C_{MEA}) - \frac{C_{MEA}}{V} \cdot \frac{dV}{dt}$
Cross-heat exchanger	
Heat balance	$\frac{dT_{r/l}}{dt} = \frac{F_{r/l}}{V_{r/l}} \cdot (T_{r_in/l_in} - T_{r/l}) \pm K_T \cdot A_T \cdot \frac{T_l - T_r}{V_r \cdot \rho_r \cdot c_{pr}}$

The heat exchanger incorporated into the process design is utilized to reuse heat from the desorption process. Assumptions for the heat exchanger model include the counter-current circulation of streams, no phase change inside the exchanger, and neglecting pressure drop and energy losses to the environment [34].

Equations describing MEA mass and heat balances within the buffer unit are provided in Table 2. Assumptions for the buffer tank system include a perfectly mixed solution, no chemical reactions, and thermal homogeneity with insulation against heat loss to the environment.

The buffer tank's design considered both investment cost and operating performance, aiming for an unchanging but reduced volume and a desired time constant of approximately half an hour. The strategy for the buffer tank incorporates MEA component concentration, temperature, and level control loops, aimed to ensure constant MEA influent parameters and promote efficient operation.

2.2. Control Strategy

The main goal of the post-combustion carbon dioxide capture facility lies in the purification of outflow gases through the retrieval and accumulation of carbon dioxide for eventual storage. Hence, the most important factor for the facility resides in the CC—carbon dioxide capture yield. CC is computed as the proportion between the quantity of captured carbon dioxide and the quantity of CO₂ introduced into the plant, computed as a percentage. This relationship is defined by the following equation:

$$CC = \frac{\text{CO}_2 \text{ (captured as outlet of the desorber)}}{\text{CO}_2 \text{ (introduced as inlet to the absorber)}} \cdot 100 \quad (1)$$

The value of the target set for CC is 90%.

Minimizing the energy penalty in the plant is also desirable. Decreasing energy usage reduces economic costs and, at the same time, lowers the intake CO₂ loading given the induced reduction of the CO₂ emissions from the power plant. The aforementioned variable can be mathematically described by the energy performance index, calculated as follows:

$$EP = \frac{Q_r}{\text{CO}_2 \text{ (captured as outlet of the desorber)}} \quad (2)$$

Here, Q_r is the heat duty to the reboiler [MW]. It is advised that the value of this index is maintained between 3–4 [MJ/kg CO₂].

The proposed MPC and PI hybrid control system design is designed to straightforwardly regulate the CO₂ capture rate of the plant. In contrast to numerous control designs for CC plants, this specific process variable is computed by taking into account the combined efficiency and dynamics of the absorber and stripper. The controlled variables (CVs), controller type and manipulated variables (MVs) are outlined in Table 3.

Table 3. CVs and MVs of the proposed control strategy.

Controlled Variable	Controller Type	Manipulated Variable
Buffer tank MEA concentration	PI	Fresh solvent flowrate
Buffer tank temperature	PI	Cooling agent flowrate
Buffer tank level	PI	Water flowrate
Carbon capture rate	MPC	Setpoint value for ratio controller
MEA to CO ₂ molar flowrate ratio	PI	Inlet liquid flow to the absorber
Reboiler liquid temperature	MPC	Reboiler heat duty (steam)

PI controllers implemented for the control loops used for the buffer tank undergo tuning via a dynamic analysis approach, subsequent to a “trial and error” adjustment protocol. This iterative process consists of changing the controller parameters based on the assessment of controlled variable responses, aimed at optimizing control performance metrics such as overshoot and response time. Tuning involves analyzing plant behavior under different operational settings and fine-tuning the controllers’ parameters to meet control goals for buffer tank level, temperature and MEA concentration.

The operation of the model predictive control controller consists of solving a series of inherent and successive optimization tasks to achieve optimal control actions that steer the controlled variables toward the desired setpoint values. Leveraging a comprehensive mathematical model, the MPC controller predicts the CO₂ capture yield and the temperature of the liquid phase in the reboiler over a defined prediction horizon, optimizing control actions to meet the control objectives. Designed for real-time operation, the MPC controller continuously updates predictions and computes the control variables based on the current system state and by considering the consequences of disturbances on the controlled variables. The MPC controller was designed to work with a prediction horizon of 10 steps and a control horizon set of 2 steps, while the sampling time was set to 180 s.

As shown in Table 3, this proposed hybrid control strategy also uses the cascade control approach, as one of the MPC controller manipulated variables is designed to adjust the setpoint of the PI ratio controller that targets the control of the ratio between the solvent molar flowrate and inlet gas molar flowrate.

The MPC was designed, and its performance was assessed for operating in two different control cases. One case implemented the minimum constrained value of 86% for the carbon capture rate and a value of 3.3 for the energy performance index, while the other one considered the case where no constraints were imposed on CC controlled variable. Both strategies were implemented using the MATLAB 2016b & Simulink 8.8 software environment.

3. Results and Discussion

The control results were analyzed in order to show the hybrid control system’s ability to achieve the influent flue gas disturbance rejection as well as keep the carbon capture rate and reboiler temperature to desired setpoints, all while managing to preserve low EP values that provide energy efficiency to the carbon capture plant. This analysis was performed by investigating two different scenarios for the presence of disturbances.

3.1. Flue Gas Flowrate Disturbance Scenario

The assessment was conducted by considering a typical disturbance of the inlet flue gas flowrate, as represented in Figure 2. It involved a 15% increase and a decrease of the same amplitude. This disturbance was aimed to assess the control system’s capability

to manage a broad range of disturbance events, such as variations in the power plant fuel composition or type, incomplete fuel combustion, power plant loading fluctuations and the imbalance of multiple steam production units of the power plant that operate simultaneously. The proposed disturbance also emulated the fluctuations in the energy requirements of the energy-producing plant that provides the inlet flue gas for the carbon capture plant.

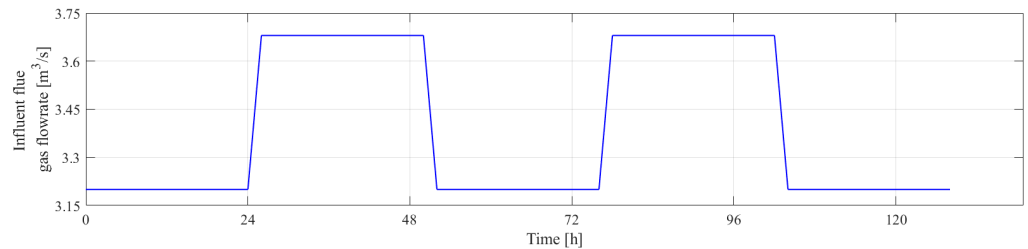


Figure 2. Inlet flue gas flowrate variation scenario.

This disturbance scenario serves to evaluate the control system's dynamic performance for rapid fluctuations of the inlet flue gas flow rate as well as for sustained periodic influent variations.

The results comparatively show the control system performance for the two considered scenarios of the constrained and unconstrained carbon capture MPC-controlled variables. The CO₂ capture rate (controlled variable), the molar ratio (manipulated variable), the liquid phase temperature in the reboiler (controlled variable), and the energy performance index are presented in Figures 3 and 4.

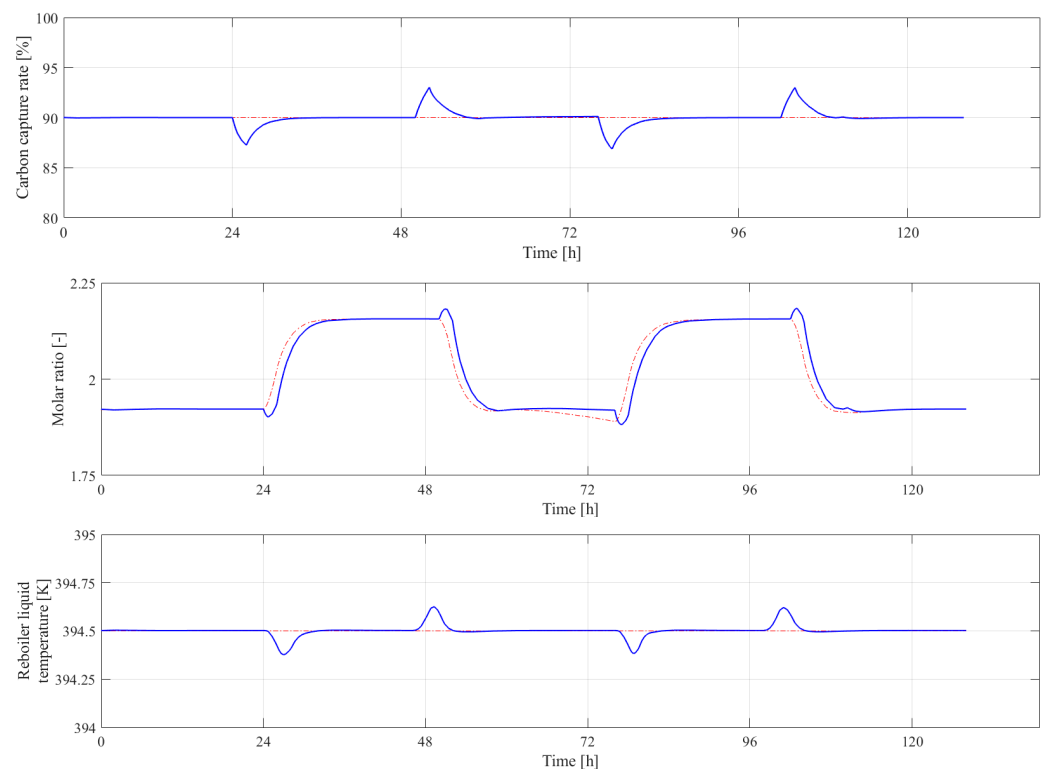


Figure 3. MPC control performance for the first disturbance scenario and the constrained MPC carbon capture control case.

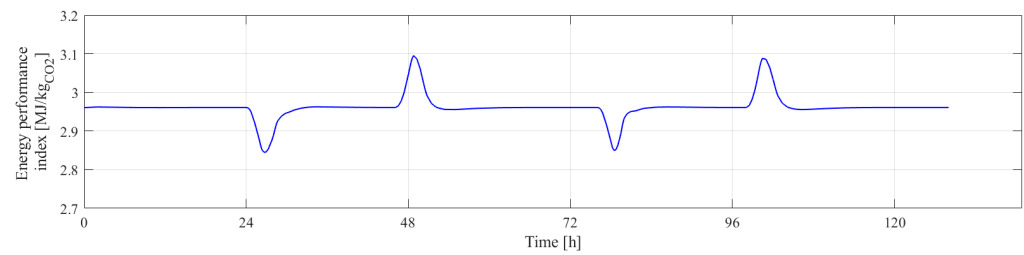


Figure 4. Energy performance index for the first disturbance scenario and constrained MPC carbon capture control case.

The control results depicted in Figure 3 demonstrate the efficiency of the hybrid control system in mitigating the undesired effects of the challenging inlet flue gas flowrate disturbances on the main carbon capture plant variables. The observed overshoot is minimal, amounting to a less than 4% increase or decrease, while the settling time is notably short. When compared with the control results of the unconstrained case in Figure 5, it can be noted that the constraint implemented within the MPC controller on the CO₂ capture rate has a favorable effect on the general efficiency of the CC plant. Controlled variables in the MPC-constrained case reveal low overshoot, reduced settling time, and diminished energy consumption.

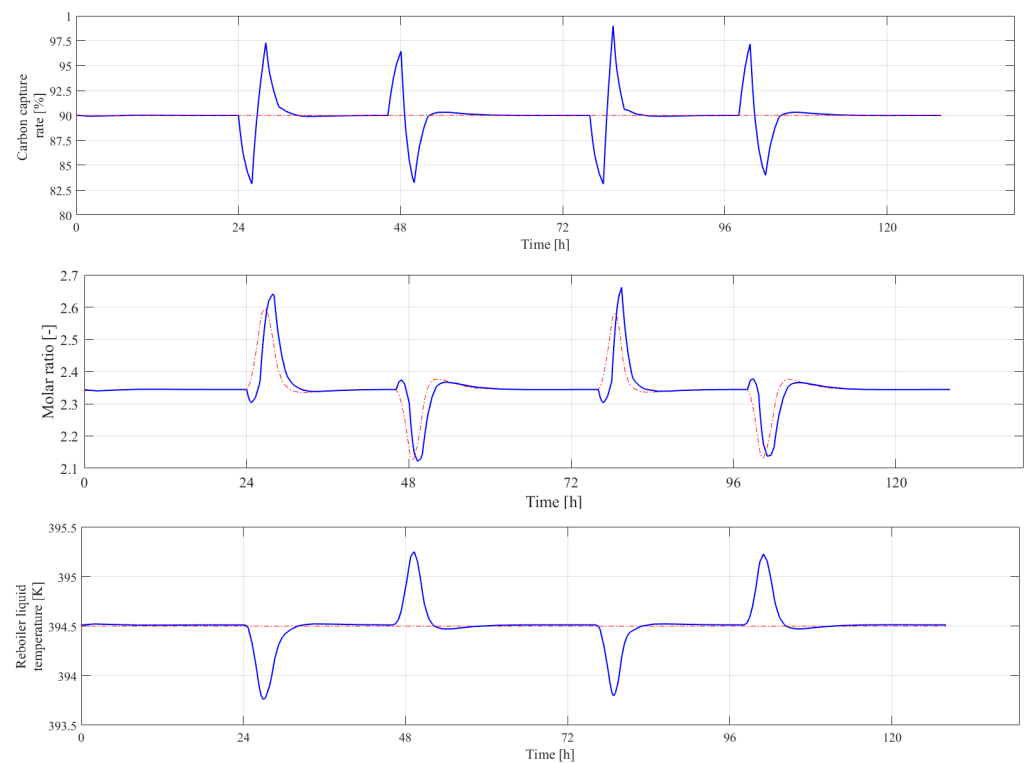


Figure 5. MPC control performance for the first disturbance scenario and the unconstrained MPC carbon capture control case.

The energy performance index, as can be observed in Figure 4, is kept below the value of 3.1 MJ/kgCO₂ at all times, despite the action of the disturbance. This can serve as proof of the MPC controller's effectiveness and demonstrates its ability to successfully satisfy operational constraints.

As shown in Figure 6, for the unconstrained MPC carbon capture control case the energy performance index was not kept below the value of 3.1 MJ/kgCO₂ at all times.

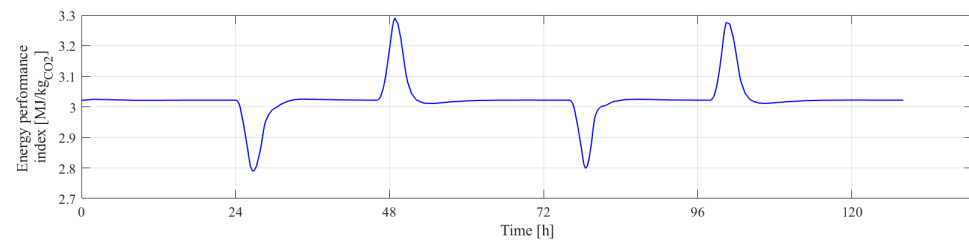


Figure 6. Energy performance index for the first disturbance scenario and the unconstrained MPC carbon capture control case.

Figure 7 illustrates the control efficiency of the buffer tank decentralized loops for the MPC-constrained case.

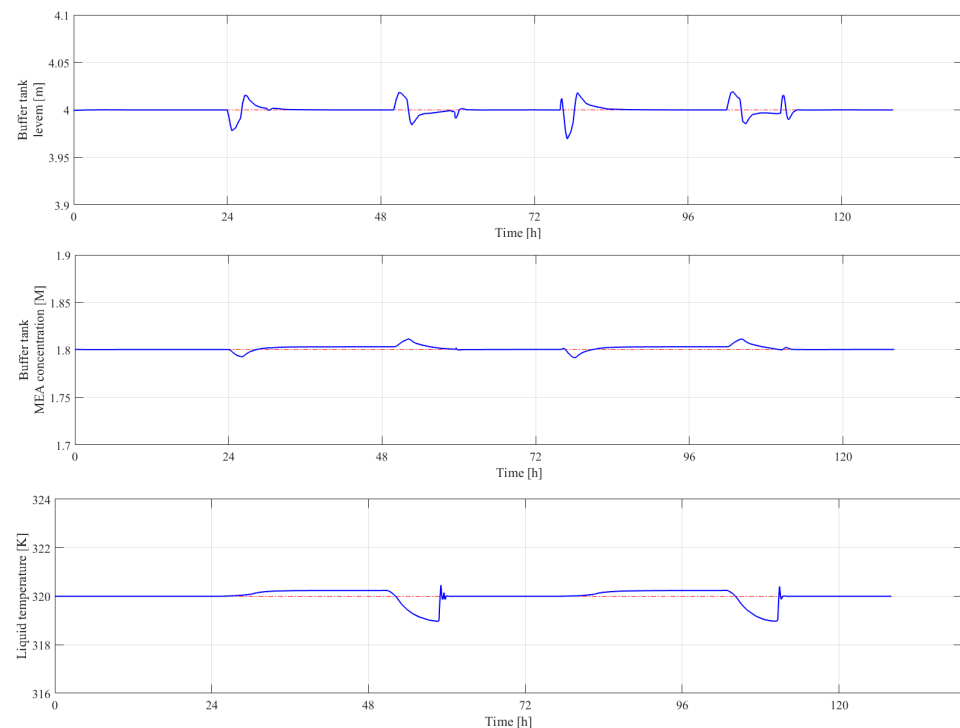


Figure 7. Buffer tank control system performance for the first disturbance scenario and the constrained MPC carbon capture control case.

As shown in Figure 7, the buffer tank decentralized control strategy is able to stabilize the desired MEA concentration, as well as temperature and level variables, despite the effects of the flue gas flowrate upsets. This approach also provides a good rejection ability of the other plant internal disturbances and prevents them from being passed onto the absorber.

This study showcases the ability of the hybrid control strategy to track the reference trajectory with good precision, as evidenced by the close alignment between the desired setpoint (represented by the red dotted line) and the actual response of the system. This highlights the controller's robustness in handling varying operating conditions and disturbances, ensuring consistent and reliable performance. Additionally, the low overshoot and minimal settling time depicted in the graphs highlights the controller's capacity to achieve stable and rapid responses. The absence of oscillations or erratic behavior further emphasizes the ability to maintain system stability in the presence of tough external disturbances.

3.2. Reboiler Heat Duty Disturbance Scenario

The second disturbance scenario consists of the reboiler heat duty undesired changes, emerging from the variations of the steam enthalpy or flowrate parameters. It is presented in Figure 8. Since the desorption process is dependent on temperature, disturbing the reboiler heat duty has a detrimental effect on the entire carbon capture process. Hence, the control strategy is expected to promptly and efficiently reject such disturbances.

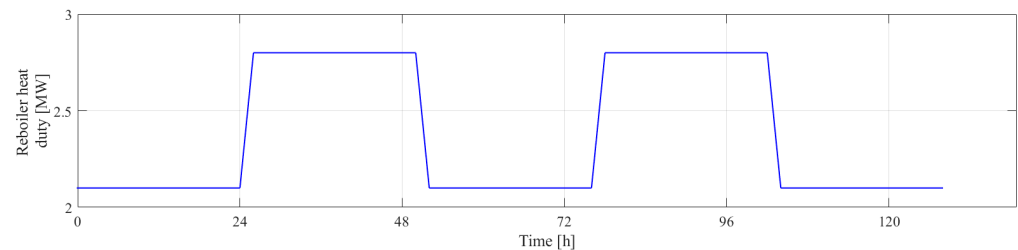


Figure 8. Reboiler heat duty disturbance.

Figures 9–11 present the results obtained using the constrained MPC and PI combined control strategies as a response to the reboiler heat duty disturbance.

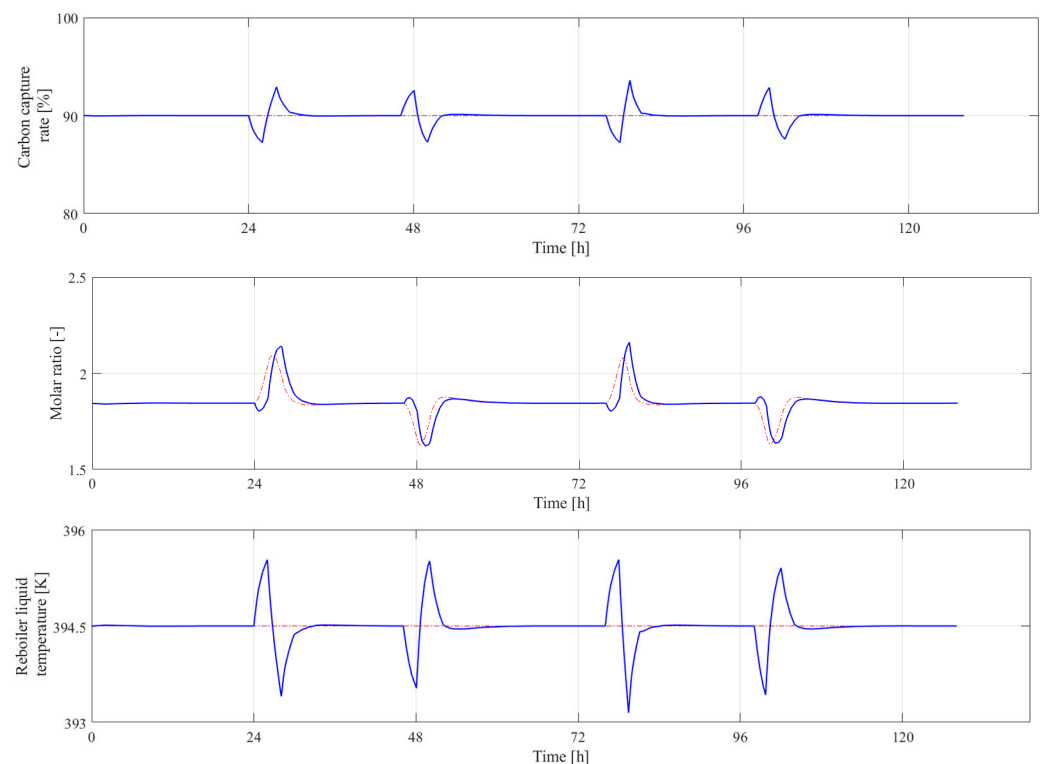


Figure 9. MPC control strategy performance for the second disturbance scenario and the constrained MPC carbon capture control case.

As can be seen in Figures 9–11, the convergence of the controlled variables to the desired setpoint is very good. It demonstrates the effectiveness of eliminating the disturbance in reduced time and with acceptable deviations from the setpoints. Additionally, while the PI controller exhibits some overshoot, it remains within acceptable limits, indicating a balanced trade-off between speed and the smoothness of the control performance. This comes in addition to the advantages of using MPC controllers, with the hybrid system proving to be a good control approach in terms of robustness, accuracy, and rapidity in counteracting disturbance effects.

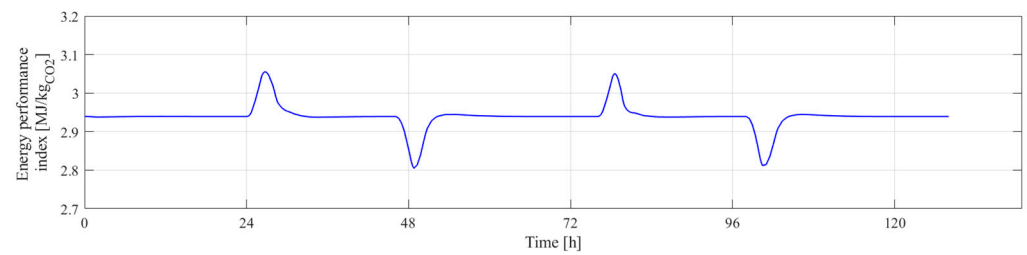


Figure 10. Energy performance index for the second disturbance scenario and the constrained MPC carbon capture control case.

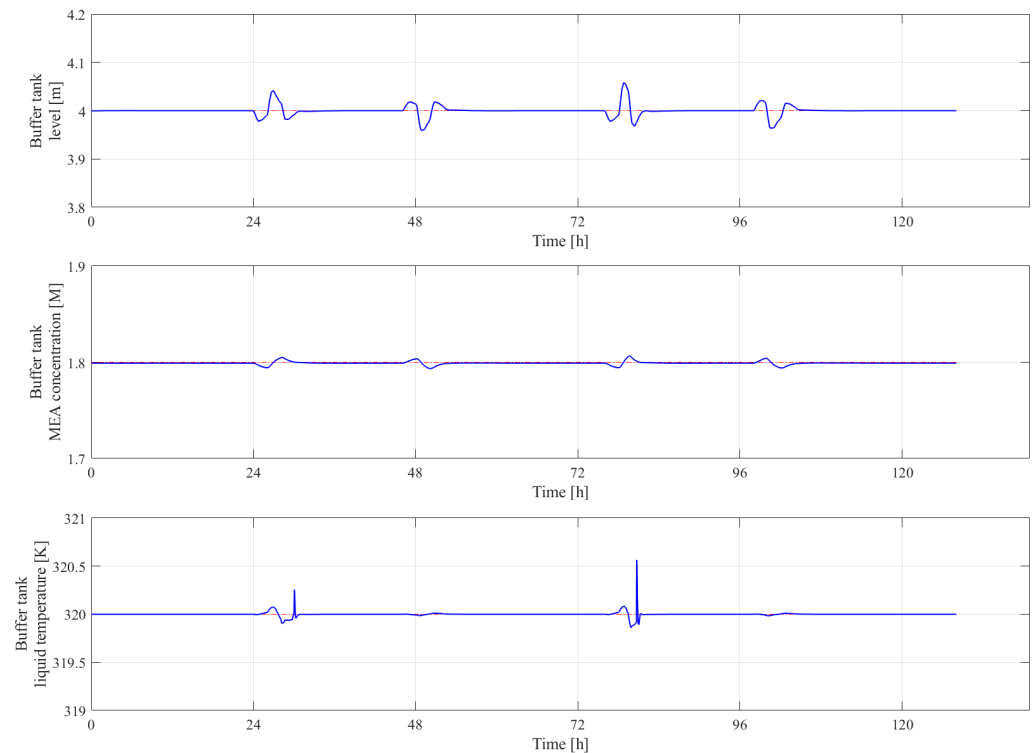


Figure 11. Buffer tank control system performance for the second disturbance scenario and the constrained MPC carbon capture control case.

3.3. Control Strategy Performance Comparison

In order to assess the performance of the MPC carbon capture hybrid control system (Case 1—present work), a comparison with three other control strategies was performed. The first one (Case 2) was a 6x6 decentralized control system that included only PI control loops and was investigated in a previous work [35]. The second one (Case 3) was a PI control system for CO₂ purity and recovery [36]. The last one (Case 4) was a PI with cascade control of the CO₂ purity [36]. The comparison was carried out in terms of settling time and overshoot for the CO₂-related controlled variables (capture rate, purity, and recovery rate). These reported control performance results considered the flue gas flowrate disturbance variation of 15% for Cases 1 and 2 and of 10% for Cases 3 and 4. The comparative results are presented in Table 4.

Table 4. Comparison of the hybrid control system performance with other control approaches.

Performance Index	Case 1	Case 2	Case 3	Case 4
Settling time	6 h	10–11 h	0.7 h	4 h
Overshoot	2.5%	3.5%	4%	3%

As can be observed from Table 4, Case 1 shows better control performance than Case 2, and has a comparable performance with Case 4. Case 3 has a very low settling time, due to a different process design, but the overshoot is slightly higher than in Case 1. However, considering that the disturbance amplitude is higher in Case 1 than in Cases 2 and 4, it can be stated that the MPC controller of the hybrid control configuration presents advantages for being used to control the CC plant. Furthermore, it may be noted that using the MPC control strategy is the most promising control approach in terms of control performance, especially due to its ability to handle process constraints systematically. This ability has been shown in the present work and has a beneficial impact on the overall control strategy performance. Moreover, the use of the multivariable control approach of the MPC controller provides an enhanced ability to consider the internal interactions between the CC plant's process variables implicitly.

4. Conclusions

The study introduced a comprehensive hybrid control strategy aimed at effectively managing the key variables of the carbon capture processes, particularly the CO₂ capture yield and the temperature of the liquid phase in the reboiler, alongside regulating the buffer tank variables, all devoted to sustaining the efficient and smooth operation of the absorber–desorber units. This control approach integrated the multivariable model predictive control with the operation of the buffer tank decentralized control loops.

Investigations were carried out for two of the most relevant disturbances, namely the influent flue gas flow rate and reboiler heat duty parameters. The MPC controller succeeded in keeping the carbon capture rate at 90% and stabilized the liquid temperature at 394.5 K in the reboiler. The hybrid MPC approach achieved reduced settling time and low overshoot performance, maintaining the controlled variables at the desired setpoints despite the action of the disturbances. The hybrid control strategy benefitted from the constraint handling ability of MPC, achieving the maintenance of the carbon capture rate above the preset minimum constrained value of 86%, while the energy performance index remained lower than the profitable value of 3.1 MJ/kgCO₂.

The hybridization of MPC and PI control techniques presented a promising approach for enhancing the performance and versatility of the control technique in the carbon capture unit. This complementarity allowed for improved performance over a wide range of operating conditions, enhancing the adaptability and resilience of the control system. Based on the synergistic combination of the MPC systematic constraints' handling capability and the PI control simplicity and robustness, the hybrid control architectures offered a flexible framework for solving challenges posed by the typical plant disturbances. These results proved the efficacy of the hybrid MPC–PI control implementation and propose it as a promising strategy for obtaining superior performance in carbon capture systems utilizing the absorption–stripping technology.

Author Contributions: Conceptualization, F.-M.I., A.-M.C. and V.M.C.; methodology, F.-M.I. and V.M.C.; software, F.-M.I. and A.-M.C.; formal analysis, C.-C.C.; investigation, F.-M.I., A.-M.C., V.M.C. and C.-C.C.; resources, A.-M.C.; writing—original draft preparation, F.-M.I. and A.-M.C.; writing—review and editing, A.-M.C., V.M.C. and C.-C.C.; visualization, F.-M.I. and A.-M.C.; supervision, V.M.C. and C.-C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This paper received no external funding.

Data Availability Statement: Data are contained within the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

A	column section [m ²]
a _e	effective mass transfer area [m ² /m ³]

A_T	heat transfer surface [m^2]
C	molar concentration [$kmol/m^3$]
C_{MEA}	MEA concentration [$kmol/m^3$]
CC	CO_2 capture rate [%]
c_p	specific heat [$kJ/kg\ K$]
EP	energy performance index [MJ/kg_{CO_2}]
F	flow rate [m^3/s]
ΔH	enthalpy [$kJ/kmol$]
K_T	heat transfer coefficient [W/m^2]
M	molar mass [$kg/kmol$]
N	molar flow [$kmol/(m^2\ s)$]
T	temperature [K]
t	time [s]
V	volume [m^3]
v	gas/liquid phase velocity [m/s]
z	space dimension [m]
Greek letters	
ρ	densities [kg/m^3]
ϑ	stoichiometric coefficients [–]
Subscript/superscript	
ag	heating/cooling agent
G	gas phase
i	regarding the chemical species: CO_2 , MEA, H_2O
j	regarding the phase: gas, liquid
l	lean solvent solution
L	liquid phase
r	rich solvent solution
R	regarding the chemical reaction
V	regarding vaporization

References

1. NASA. Available online: <https://climate.nasa.gov> (accessed on 29 March 2023).
2. Khallaghi, N.; Hanak, D.P.; Manovic, V. Techno-economic evaluation of near-zero CO_2 emission gas-fired power generation technologies: A review. *J. Nat. Gas. Sci. Eng.* **2020**, *74*, 103095. [\[CrossRef\]](#)
3. Ember. Available online: <https://ember-climate.org/data/data-tools/carbon-price-viewer/> (accessed on 2 January 2023).
4. Poelhekke, S. How expensive should CO_2 be? Fuel for the political debate on optimal climate policy. *Heliyon* **2019**, *5*, e02936. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Rennert, K.; Errickson, F.; Prest, B.C.; Rennels, L.; Newell, R.G.; Pizer, W.; Kingdon, C.; Wingenroth, J.; Cooke, R.; Parthum, B.; et al. Comprehensive evidence implies a higher social cost of CO_2 . *Nature* **2022**, *610*, 687–692. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Chételat, J.; McKinney, M.A.; Amyot, M.; Dastoor, A.; Douglas, T.A.; Heimbürger-Boavida, L.-E.; Kirk, J.; Kahilainen, K.K.; Outridge, P.M.; Pelletier, N.; et al. Climate change and mercury in the Arctic: Abiotic interactions. *Sci. Total Environ.* **2022**, *824*, 153715. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Alhamid, A.K.; Akiyama, M.; Aoki, K.; Koshimura, S.; Frangopol, D.M. Stochastic renewal process model of time-variant tsunami hazard assessment under nonstationary effects of sea-level rise due to climate change. *Struct. Saf.* **2022**, *99*, 102263. [\[CrossRef\]](#)
8. Ye, C.; Ye, Q.; Shi, X.; Sun, Y. Technology gap, global value chain and carbon intensity: Evidence from global manufacturing industries. *Energy Pol.* **2020**, *137*, 111094. [\[CrossRef\]](#)
9. Wang, K.; Mao, Y.; Chen, J.; Yu, S. The optimal research and development portfolio of low-carbon energy technologies: A study of China. *J. Clean. Prod.* **2018**, *176*, 1065–1077. [\[CrossRef\]](#)
10. Impram, S.; Nese, S.V.; Oral, B. Challenges of renewable energy penetration on power system flexibility: A survey. *Energy Strategy Rev.* **2020**, *31*, 100539. [\[CrossRef\]](#)
11. Khosroabadi, F.; Aslani, A.; Bekhrad, K.; Zolfaghari, Z. Analysis of carbon dioxide capturing technologies and their technology developments. *Clean. Eng. Technol.* **2021**, *5*, 100279. [\[CrossRef\]](#)
12. Akachuku, A.; Osei, P.A.; Decardi-Nelson, B.; Srisang, W.; Pouryousefi, F.; Ibrahim, H.; Idem, R. Experimental and kinetic study of the catalytic desorption of CO_2 from CO_2 -loaded monoethanolamine (MEA) and blended monoethanolamine-Methyldiethanolamine (MEA-MDEA) solutions. *Energy* **2019**, *179*, 475–489. [\[CrossRef\]](#)
13. Ostace, G.S.; Cristea, V.M.; Agachi, P.S. Investigation of Different Control Strategies for the BSM1 Waste Water Treatment Plant with Reactive Secondary Settler Model. In *ESCAPE 20, Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2010; Volume 28, pp. 1841–1847, ISBN 978-0-444-53718-8.

14. Cristea, V.M. Counteracting the accidental pollutant propagation in a section of the River Someş by automatic control. *J. Environ. Manag.* **2013**, *128*, 828–836. [[CrossRef](#)] [[PubMed](#)]
15. Iancu, M.; Cristea, M.V.; Agachi, P.S. MPC vs. PID. The advanced control solution for an industrial heat integrated fluid catalytic cracking plant. In *Computer Aided Chemical Engineering*; Pistikopoulos, E.N., Georgiadis, M.C., Kokossis, A.C., Eds.; Elsevier: Amsterdam, The Netherlands, 2011; Volume 29, pp. 517–521. [[CrossRef](#)]
16. He, Z.; Sahraei, M.H.; Ricardez-Sandoval, L.A. Flexible operation and simultaneous scheduling and control of a CO₂ capture plant using model predictive control. *Int. J. Greenh. Gas. Control* **2016**, *48*, 300–311. [[CrossRef](#)]
17. Huba, M.; Chamraz, S.; Bistak, P.; Vrancic, D. Making the PI and PID Controller Tuning Inspired by Ziegler and Nichols Precise and Reliable. *Sensors* **2021**, *21*, 6157. [[CrossRef](#)] [[PubMed](#)]
18. Gaspar, J.; Jorgensen, J.B.; Fosbol, P.L. Control of a post-combustion CO₂ capture plant during process start-up and load variations. *IFAC-PapersOnLine* **2015**, *48*, 580–585. [[CrossRef](#)]
19. Mehleri, E.D.; Mac Dowell, N.; Thornhill, N.F. Model predictive control of postcombustion CO₂ capture process integrated with a power plant. In *Computer Aided Chemical Engineering*; Gernaey, K.V., Huusom, J.K., Gani, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2015; Volume 37, pp. 161–166. [[CrossRef](#)]
20. Panahi, M.; Skogestad, S. Economically efficient operation of CO₂ capturing process part I: Self-optimizing procedure for selecting the best controlled variables. *Chem. Eng. Process Process Intensif.* **2011**, *50*, 247–253. [[CrossRef](#)]
21. Nebeluk, R.; Ławryńczuk, M. Tuning of Multivariable Model Predictive Control for Industrial Tasks. *Algorithms* **2021**, *14*, 10. [[CrossRef](#)]
22. Lin, Y.-J.; Pan, T.-H.; Wong, D.S.-H.; Jang, S.-S.; Chi, Y.-W.; Yeh, C.-H. Plantwide control of CO₂ capture by absorption and stripping using monoethanolamine solution. *Ind. Eng. Chem. Res.* **2011**, *50*, 1338–1345. [[CrossRef](#)]
23. Domański, P.D. Performance Assessment of Predictive Control—A Survey. *Algorithms* **2020**, *13*, 97. [[CrossRef](#)]
24. Robinson, P.J.; Luyben, W.L. Integrated gasification combined cycle dynamic model: H₂S absorption/stripping, Water– Gas shift reactors, and CO₂ absorption/stripping. *Ind. Eng. Chem. Res.* **2010**, *49*, 4766–4781. [[CrossRef](#)]
25. Arce, A.; Mac Dowell, N.; Shah, N.; Vega, L.F. Flexible operation of solvent regeneration systems for CO₂ capture processes using advanced control techniques: Towards operational cost minimisation. *Int. J. Greenh. Gas. Control* **2012**, *11*, 236–250. [[CrossRef](#)]
26. Sahraei, M.H.; Ricardez-Sandoval, L.A. Controllability and optimal scheduling of a CO₂ capture plant using model predictive control. *Int. J. Greenh. Gas. Control* **2014**, *30*, 58–71. [[CrossRef](#)]
27. Dutta, R.; Nord, L.O.; Bolland, O. Prospects of using equilibrium-based column models in dynamic process simulation of post-combustion CO₂ capture for coal-fired power plant. *Fuel* **2017**, *202*, 85–97. [[CrossRef](#)]
28. Gáspár, J.; Cormos, A.M. Dynamic modeling and validation of absorber and desorber columns for post-combustion CO₂ capture. *Comput. Chem. Eng.* **2011**, *35*, 2044–2052. [[CrossRef](#)]
29. Gáspár, J.; Cormos, A.M. Assessment of mass transfer and hydraulic aspects of CO₂ absorption in packed columns. *Int. J. Greenh. Gas. Control* **2012**, *6*, 201–209.
30. Versteeg, G.F.; Van Dijk, L.A.J.; Van Swaaij, W.P.M. On the kinetics between CO₂ and alkanolamines both in aqueous and non-aqueous solutions. An overview. *Chem. Eng. Commun.* **1996**, *144*, 113–158. [[CrossRef](#)]
31. Rocha, J.A.; Bravo, J.L.; Fair, J.R. Distillation columns containing structured packings: A comprehensive model for their performance. 1. Hydraulic models. *Ind. Eng. Chem. Res.* **1993**, *32*, 641–651. [[CrossRef](#)]
32. Rocha, J.A.; Bravo, J.L.; Fair, J.R. Distillation columns containing structured packings: A comprehensive model for their performance. 2. Mass-transfer model. *Ind. Eng. Chem. Res.* **1996**, *35*, 1660–1667. [[CrossRef](#)]
33. Wang, C.; Xu, Z.; Lai, C.; Sun, X. Beyond the standard two-film theory: Computational fluid dynamics simulations for carbon dioxide capture in a wetted wall column. *Chem. Eng. Sci.* **2018**, *184*, 103–110. [[CrossRef](#)]
34. Cristea, V.M.; Burca, M.I.; Ilea, F.M.; Cormos, A.M. Efficient decentralized control of the post combustion CO₂ capture plant for flexible operation against influent flue gas disturbances. *Energy* **2020**, *205*, 117960. [[CrossRef](#)]
35. Ilea, F.M.; Cormos, A.M.; Cristea, V.M.; Cormos, C.C. Enhancing the post-combustion carbon dioxide carbon capture plant performance by setpoints optimization of the decentralized multi-loop and cascade control system. *Energy* **2023**, *275*, 127490. [[CrossRef](#)]
36. Skjervold, V.T.; Mondino, G.; Riboldi, L.; Nord, L.O. Investigation of control strategies for adsorption-based CO₂ capture from a thermal power plant under variable load operation. *Energy* **2023**, *268*, 126728. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.