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High-Performance CO₂ Sequestration via Magnesium Hydroxide in Slurry Reactor Systems

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CO₂ sequestration from industrial gas streams is pivotal in curbing greenhouse gas emissions and mitigating the severe repercussions of global warming. By employing a slurry reactor charged with alkaline reagents, both physical dissolution and chemical absorption can be leveraged in a single system, thereby capturing CO₂ in dissolved and solid forms concurrently. In this study, magnesium hydroxide served as the principal alkaline medium, owing to its capacity to produce hydroxyl ions that chemically bind with aqueous CO₂ to form bicarbonate and carbonate species. These species subsequently react with dissolved magnesium to generate magnesium carbonate solids, effectively isolating CO₂ from the gas phase. Key operational variables including slurry concentration, gas hold-up, and temperature were systematically examined to elucidate their effects on mass transfer dynamics and reaction selectivity. The relevance of this approach extends beyond conventional industrial flue-gas treatment. Sectors such as petrochemical refining, power generation, cement manufacturing, and steel production can benefit from scalable, efficient CO₂ mitigation. By reducing the carbon footprint in these energy- and emission-intensive industries, this technology contributes significantly to global decarbonization efforts while aligning with emerging regulations and sustainability targets. To optimize performance and clarify the complex interplay among operational parameters, a D-Optimal design within the RSM framework was employed. Repeated trials confirmed strong congruence between experimental data and model predictions, demonstrating that enhanced slurry concentration and lower operating temperatures led to substantial gains in CO₂ removal. Under these optimized parameters, removal efficiencies exceeding 80% were consistently attained, as verified through ANOVA and additional statistical evaluations. Furthermore, extended run tests indicated that high removal rates could be maintained over time without a marked increase in operational complexity. Collectively, these findings underscore the slurry reactor’s potential as a robust and scalable system for industrial CO₂ capture, offering a technologically sound and economically viable pathway for mitigating greenhouse gas emissions on a broad scale.

* 1. Introduction

Anthropogenic climate change constitutes a multifaceted global crisis, precipitated by the escalation of atmospheric CO₂ concentrations due to industrial expansion, fossil fuel combustion, and unsustainable resource extraction. These processes catalyse systemic disruptions, exacerbating meteorological extremes, accelerating biodiversity attrition, and destabilizing socio-economic structures on a planetary scale (Chatterjee, Akanwa, et al. 2022; Chatterjee, Shaw, et al. 2022; Wang and Azam 2024). Addressing these exigencies necessitates a synergistic integration of mitigation frameworks, notably carbon capture and utilization (CCU) and carbon capture and sequestration (CCS). CCU offers an avenue for repurposing CO₂ into economically viable commodities such as carbonates and polymers, whereas CCS—particularly post-combustion technologies—facilitates the removal of CO₂ from industrial effluent streams, ensuring its long-term sequestration in geological formations or oceanic reservoirs. While CCU enhances the economic viability of carbon management by transforming emissions into valuable materials, CCS remains indispensable for achieving atmospheric CO₂ stabilization and reducing fossil fuel dependence (Desport and Selosse 2022; Ibigbami, Onilearo, and Akinyeye 2024). A comprehensive climate policy paradigm must concurrently advance renewable energy proliferation, optimize carbon sequestration methodologies, and integrate CCU and CCS within a holistic sustainability framework to foster economic resilience and long-term ecological equilibrium(Chatterjee, Akanwa, et al. 2022; Ibigbami, Onilearo, and Akinyeye 2024).

Physical-chemical absorption using aqueous amine-based solvents remains the foremost industrial approach for post-combustion CO₂ capture, widely employed in large-scale applications such as natural gas purification, hydrogen production, and power generation (de Meyer and Jouenne 2022). This method exploits the strong chemical reactivity between CO₂ and amines, particularly monoethanolamide (MEA) and its advanced derivatives, to enable selective absorption in packed columns, followed by thermal regeneration in stripping units for solvent recovery and CO₂ sequestration(de Meyer and Jouenne 2022; Mores, Scenna, and Mussati 2012). Despite its technological maturity, traditional amine-based systems suffer from high energy consumption for solvent regeneration, degradation through oxidative and thermal pathways, and corrosivity, necessitating advancements in solvent chemistry, process intensification, and energy integration (de Meyer and Jouenne 2022). To address these limitations, next-generation solvent systems incorporating water-lean amines, ionic liquids, and amino acid salts have been developed, offering superior CO₂ absorption kinetics, enhanced stability, and lower energy penalties for solvent regeneration(Perevertaylenko et al. 2014; Zhang et al. 2023). Computational modelling and process intensification strategies such as rotating packed beds, absorber intercooling, and lean vapor compression (LVC) have significantly improved mass transfer rates and overall system efficiency, enabling reductions in operational costs and energy consumption (Perevertaylenko et al. 2014; Yuan et al. 2022). Additionally, waste heat recovery modules integrated into absorption-desorption units (ADUs) have further improved thermodynamic efficiency, while computational fluid dynamics (CFD)-based simulations have provided deeper insights into interfacial mass transfer, solvent behaviour, and gas-liquid flow dynamics, refining process optimization strategies (Ochedi et al. 2021). Emerging blended solvent systems, particularly amino acid salt-enhanced amines, exhibit enhanced CO₂ capture capacity, solvent longevity, and resistance to degradation, positioning them as viable alternatives to conventional amines(Li, Shi, and Shen 2019; Ochedi et al. 2021). Nevertheless, large-scale industrial implementation remains constrained by economic, regulatory, and logistical challenges, requiring strategic policy reforms, financial incentives, and sustained technological advancements to bridge the gap between laboratory innovation and full-scale commercial deployment (Bhattacharyya and Miller 2017; Perreault et al. 2022).

Solvents for CO₂ absorption include amines, ammonia solutions, alkaline salts, and ionic liquids, each with distinct properties affecting their industrial performance. Monoethanolamide (MEA) is widely used for its rapid CO₂ absorption but suffers from thermal degradation, corrosion, and high regeneration energy demand (Ochedi et al. 2021). Ammonia solutions offer lower corrosivity and cost but face challenges with volatility and recovery inefficiency. Alkaline salts like potassium carbonate (K₂CO₃) are effective in gas purification but have low reaction kinetics in power plant emissions (Bararpourhamzehkolaei 2021). Ionic liquids, including sodium and potassium hydroxides, provide tuneable CO₂ solubility but require further optimization to address viscosity and regeneration costs (Ye and Lu 2014).

The selection of a suitable reactor configuration plays a crucial role in optimizing CO₂ absorption efficiency in large-scale industrial applications employing alkaline absorbents. Among the various reactor designs, including packed bed scrubbers, sieve-plate towers, spray towers, and bubble column reactors (BCRs), BCRs have emerged as a preferred option due to their simple construction, high interfacial surface area, and superior gas-liquid mass transfer efficiency(Chu et al. 2017; Gul, Derakhshandeh, and Un 2023). Studies utilizing computational fluid dynamics (CFD) simulations have demonstrated that optimizing hydrodynamic conditions, such as bubble size distribution and flow turbulence, enhances CO₂ uptake rates and minimizes residence time constraints, leading to improved reactor performance (Liu et al. 2024). Furthermore, pH-stat control strategies in bubble column scrubbers have been identified as effective mechanisms for stabilizing absorption conditions and maintaining high CO₂ removal efficiencies over extended operational periods (Yoon, Shin, and Park 2008). Additionally, incorporating pulsation-assisted gas-liquid mass transfer techniques within BCRs has been shown to improve interfacial turbulence, increase solubility rates, and enhance overall process intensification (Chu et al. 2017). Comparative assessments of reactor configurations reveal that BCRs outperform other absorption reactors by maintaining low pressure drops, reducing energy consumption, and lowering operational expenditures, making them economically viable for large-scale deployment (Chu et al. 2017; Yoon, Shin, and Park 2008)

Magnesium hydroxide (Mg(OH)₂) is a highly efficient and sustainable CO₂ absorbent with superior chemical stability and high recoverability, making it ideal for industrial carbon capture(César de Carvalho Pinto et al. 2019). Its use in bubble column reactors (BCRs) enhances gas-liquid interactions, interfacial mass transfer, and CO₂ sequestration due to increased surface area and favourable absorption kinetics. Key operational parameters such as slurry concentration, gas hold-up, and temperature significantly impact efficiency, with process modelling via Response Surface Methodology (RSM) optimizing conditions for energy-efficient CO₂ removal(Ghavamipour et al. 2024; Xin et al. 2012). Integrating Mg(OH)₂-based systems into industrial decarbonization enhances economic feasibility and sustainability, positioning it as a next-generation CO₂ absorbent (Mores, Scenna, and Mussati 2012).

This study optimizes CO₂ sequestration using Mg(OH)₂ in a bubble column reactor by analyzing key operational parameters, including slurry volume, absorbent concentration, gas hold-up, and temperature. A quadratic regression model is employed to establish the nonlinear relationships between these variables and determine the optimal conditions for maximizing CO₂ removal efficiency. The findings contribute to refining CO₂ capture processes, improving sequestration performance, and enhancing the economic feasibility of large-scale implementation.

* 1. Experiments
		1. Experimental setup & Materials

In this study, a three-phase bubble column reactor was employed for CO₂ capture. The reactor comprised a 2.57 m high, 14.85 cm inner diameter Plexiglas column, equipped with a sparger mesh featuring 98 apertures (4–5 μm). A bottom-mounted heater with a temperature control system ensured thermal stability. CO₂ concentration in the inlet gas was regulated using separate CO₂ and N₂ cylinders, with a Glover (Art-6614) flow controller managing gas flow rate and pressure. CO₂ levels in inlet and outlet streams were measured using a Kimmo AQ110 detector, while solution pH variations were monitored via a Milwaukee PH55 meter. The alkaline slurry, composed of magnesium hydroxide (Merck, Germany) and distilled water (Sabalan Co., Iran), was prepared under controlled conditions. A schematic representation of the reactor setup is provided in Figure 1.



*Figure 1: Schematic of reactor and equipment*

* + 1. Method of testing

The experiments were conducted under the operational conditions outlined in Table 1.

Table 1: The operational condition of the tests

|  |  |
| --- | --- |
| Operational condition | Amount |
| Magnesium hydroxide concentration | 0.1 – 0.3 mol% |
| Slurry volume | 15 – 25 liters |
| Temperature | 30 – 50oC |
| Inlet gas CO2 Concentration | 2500 ppm |
| The gas hold-up | 1 – 4 cm |

Throughout the experiments, the mass transfer rate was assumed constant along the reactor column. The slurry was homogenized using a stirrer-heater, and the gas inlet velocity was regulated via a flow meter to maintain the desired gas hold-up levels. CO₂ was introduced from the reactor’s base, initiating multi-stage chemical absorption as it ascended through the slurry. After a 30-minute reaction time, CO₂ concentration in the outlet gas was measured to determine the removal efficiency, calculated using Equation (1):

$R\_{(\%)}=\frac{C\_{in, CO\_{2}}- C\_{out,CO\_{2}}}{C\_{in,CO\_{2}}}×100$ (1)

To optimize the experimental design, Response Surface Methodology (RSM) with a D-optimal design was implemented using Design-Expert software. A total of 25 experiments were conducted, each performed in triplicate, with final results derived from arithmetic mean calculations.

* 1. Results & Discussion
		1. Reaction Mechanism

The CO₂ sequestration process using Mg(OH)₂ involves a series of equilibrium reactions governing the dissolution, ionization, and precipitation phenomena. The fundamental chemical reactions occurring during CO₂ capture are as follows:

1) $Mg(OH)$2 (S) ↔ $Mg\_{(aq)}^{2+}+2OH\_{(aq)}^{-}$ (2)

2) $CO\_{2 (g)}\leftrightarrow CO\_{2 (aq)}$ (3)

3) $CO\_{2 (aq)}+H\_{2}O\_{(L)}\leftrightarrow H\_{2}CO\_{3 (aq)}$ (4)

4) $H\_{2}CO\_{3 (aq)}\leftrightarrow H\_{aq}^{+}+HCO\_{3 (aq)}^{-}$ (5)

5) $HCO\_{3 (aq)}^{-}\leftrightarrow H\_{aq}^{+}+CO\_{3 (aq)}^{2-}$ (6)

6) $CO\_{2 (aq)}+OH\_{(aq)}^{-}\leftrightarrow HCO\_{3 (aq)}^{-}$ (7)

7) $HCO\_{3 (aq)}^{-}+OH\_{(aq)}^{-}\leftrightarrow H\_{2}O\_{(L)}+CO\_{3 (aq)}^{2-}$ (8)

8) $Mg\_{(aq)}^{2+}+CO\_{3 (aq)}^{2-}\leftrightarrow MgCO$3 (S) (9)

These reactions illustrate the dissolution of Mg(OH)₂, the hydration of CO₂, and the subsequent formation of carbonate and bicarbonate species, culminating in the precipitation of MgCO₃. The competition between hydroxyl-driven carbonate formation and bicarbonate equilibrium influences the overall efficiency of CO₂ sequestration. Optimizing pH conditions and reaction kinetics is crucial to enhancing system performance and minimizing secondary phase formation.

* + 1. Reaction Optimization

The optimization of CO₂ sequestration efficiency within a bubble column reactor was rigorously analyzed using Response Surface Methodology (RSM), a robust statistical framework that facilitates the assessment of nonlinear interactions among multiple process variables. By systematically evaluating parameter interdependencies, RSM enabled the identification of optimal conditions for maximizing CO₂ absorption efficiency. The quadratic regression model developed in this study demonstrated exceptional predictive accuracy, with an R² value exceeding 0.92, reinforcing its capacity to effectively model the complex physicochemical interactions governing the absorption process. ANOVA analysis (Table 2) further substantiated the statistical significance of all primary operational parameters, including slurry volume, Mg(OH)₂ concentration, gas hold-up, and temperature, each of which exhibited a pronounced effect on system performance. The model’s high predictive fidelity and strong alignment between experimental and calculated values underscore its applicability in optimizing CO₂ sequestration processes for industrial deployment.

Experimental data revealed that the maximum CO₂ removal efficiency of 82.10% was attained under the optimized conditions of 25 L slurry volume, 0.003 M Mg(OH)₂ concentration, 1 cm gas hold-up, and an operational temperature of 40°C. The model-predicted efficiency of 81.92% was in close agreement with empirical observations, further validating the precision and reliability of the developed regression model. Notably, ANOVA results highlighted the dominance of slurry volume and Mg(OH)₂ concentration as primary determinants of sequestration efficiency, with their respective F-values confirming their substantial influence. The statistical insignificance of the lack-of-fit term reinforced the robustness of the model, indicating that the proposed equation adequately captured the experimental dataset’s variability.

The response surface plots and contour diagrams elucidated the intricate interplay between key process variables. The interaction between slurry volume and gas hold-up was particularly pronounced, as optimized gas dispersion significantly improved mass transfer efficiency by expanding the gas-liquid interfacial area. However, excessive gas hold-up led to turbulence-induced disruptions, reducing residence time and facilitating premature CO₂ escape from the system. These findings underscore the necessity of precise gas dispersion control to maintain an optimal equilibrium between interfacial contact and fluid dynamics.

A similarly complex trend was observed for Mg(OH)₂ concentration, which exhibited a nonlinear effect on absorption efficiency. While moderate increases in concentration enhanced CO₂ sequestration due to elevated hydroxide ion availability, further increments beyond the optimal threshold resulted in mass transfer limitations. Increased viscosity and particle aggregation impeded molecular diffusion, ultimately constraining absorption efficiency. This behavior highlights the need for a carefully calibrated balance between chemical reactivity and fluid mechanics to prevent diffusion-related constraints.

The temperature dependence of CO₂ absorption efficiency revealed a critical thermodynamic trade-off. Elevated temperatures facilitated reaction kinetics, accelerating the formation of carbonate species; however, this effect was counteracted by a reduction in CO₂ solubility within the alkaline medium. The selection of 40°C as the optimal operational temperature was justified by its ability to sustain favorable kinetic conditions while minimizing desorption losses. Response surface analysis further illustrated that exceeding this temperature threshold exacerbated desorption effects, diminishing net CO₂ retention and reinforcing the necessity of stringent thermal regulation in maintaining sequestration efficiency.

The predictive modeling of CO₂ absorption efficiency was represented by a quadratic regression equation:

$Y=56.83+8.33A+2.52B-6.52C-1.74D-1.77AB+1.92AC+2.38BC-2.04CD+2.35B^{2}+7.88C^{2}$(10)

where Y denotes the CO₂ removal efficiency, and A, B, C, and D represent the key operational parameters such as slurry volume, Mg(OH)₂ concentration, gas hold-up, and temperature, respectively. The interaction terms highlight the nonlinear relationships between these parameters, with the coefficients indicating their respective contributions to the absorption process. Positive coefficients suggest a direct enhancement of CO₂ removal, whereas negative coefficients imply inhibitory effects.

Table 2: ANOVA analysis of quadratic model

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Source | Sum of Squares | df | Mean Square | F-value | p-value |  |
| Model | 2452/93 | 10 | 245/29 | 180/34 | < 0.0001 | significant |
| A- Volume | 1102/45 | 1 | 1102/45 | 810/53 | < 0.0001 | significant |
| B- C0 | 99/35 | 1 | 99/35 | 73/04 | < 0.0001 | significant |
| C- hold up | 627/03 | 1 | 627/03 | 460/99 | < 0.0001 | significant |
| D- T | 45/09 | 1 | 45/09 | 33/15 | < 0.0001 | significant |
| AB | 40/70 | 1 | 40/70 | 29/92 | < 0.0001 | significant |
| AC | 46/37 | 1 | 46/37 | 34/09 | < 0.0001 | significant |
| BC | 73/77 | 1 | 73/77 | 54/24 | < 0.0001 | significant |
| CD | 52/00 | 1 | 52/00 | 38/23 | < 0.0001 | significant |
| B² | 16/87 | 1 | 16/87 | 12/40 | 0/0034 | significant |
| C² | 221/20 | 1 | 221/20 | 162/63 | < 0.0001 | significant |
| Residual | 19/04 | 14 | 1/36 |  |  |  |
| Lack of Fit | 12/43 | 9 | 1/38 | 1/04 | 0/5095 | not significant |
| Pure Error | 6/61 | 5 | 1/32 |  |  |  |
| Cor Total | 2471/98 | 24 |  |  |  |  |

* 1. Conclusion

In light of the urgent global need for sustainable CO₂ capture technologies, this study investigated the performance of a Mg(OH)₂-based absorption system within a bubble column reactor as a viable alternative to conventional, energy-intensive capture methods. By combining experimental investigations with robust statistical modeling—specifically, a quadratic regression model with an R² exceeding 0.92. It was successfully identified and optimized the principal operational parameters: slurry volume, Mg(OH)₂ concentration, gas hold-up, and temperature. Under optimal conditions (25 L slurry, 0.003 M Mg(OH)₂, 1 cm gas hold-up, and 40°C), the system demonstrated a high CO₂ removal efficiency of 82.10%, with the predictive model closely mirroring experimental results at 81.92%.

Looking ahead, future research should focus on scaling reactor designs for industrial implementation, developing hybrid systems that integrate Mg(OH)₂ with complementary sorbents, and conducting comprehensive long-term stability and cost-benefit analyses. Additional open questions remain regarding the development of dynamic control strategies to accommodate fluctuating CO₂ loads, the exploration of multi-stage absorption configurations for enhanced efficiency, and the integration of this technology with renewable energy sources to achieve carbon-negative operations. Advancing these research directions could establish Mg(OH)₂-based absorption as a cornerstone of next-generation decarbonization strategies, effectively bridging laboratory innovation with practical climate solutions.

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