CO_2 Capture from Cement Kiln Flue Gas Using Chemical Absorption

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Abstract - ***The cement industry is a major source of carbon dioxide emissions due to both fossil fuel combustion and the calcination of limestone during clinker production. Mitigating CO_2 emissions from cement kiln flue gas is therefore critical for achieving environmental sustainability in the construction sector. Chemical absorption is one of the most mature and effective post-combustion CO_2 capture technologies and is particularly suitable for treating flue gases with relatively high CO_2 concentrations, such as those from cement kilns. In this study, CO_2 capture from cement kiln flue gas using amine-based chemical absorption is investigated. Monoethanolamine (MEA) is employed as the primary absorbent due to its high reactivity with CO_2 and established industrial usage. The influence of key operating parameters, including solvent concentration, gas–liquid contact conditions, and regeneration requirements, on CO_2 removal efficiency is examined. Process performance is evaluated based on capture efficiency and energy demand associated with solvent regeneration. The study highlights the feasibility of chemical absorption as a viable CO_2 mitigation strategy for the cement industry and provides valuable insights into operational factors affecting absorption efficiency and energy consumption. The findings contribute to the understanding of post-combustion carbon capture processes applicable to cement manufacturing***.

Index Terms: **CO_2 capture; Cement kiln flue gas; Chemical absorption; Monoethanolamine (MEA); Post-combustion capture; Cement industry emissions**

I. INTRODUCTION

The cement industry plays a crucial role in global infrastructure development; however, it is also one of the most energy-intensive and carbon-emitting industrial sectors. The production of ordinary Portland cement involves high-temperature processes, particularly clinker formation in rotary kilns, which result in substantial carbon dioxide (CO_2) emissions. Unlike many other industries, CO_2 emissions from cement manufacturing originate not only from the combustion of fossil fuels but also from the calcination of limestone, an unavoidable chemical reaction that releases CO_2 [1-2]. As a result, the cement sector is responsible for approximately 7–8% of global anthropogenic CO_2 emissions, making it a significant target for emission reduction strategies.

Increasing global demand for cement, driven by urbanization and infrastructure expansion, has intensified concerns regarding the environmental impact of cement production. Regulatory pressure, international climate commitments, and the growing emphasis on sustainable construction have encouraged the cement industry to explore effective CO_2 mitigation technologies. While improvements in energy efficiency, fuel substitution, and the use of supplementary cementitious materials can partially reduce emissions, these measures alone are insufficient to achieve deep decarbonization. Consequently, carbon capture technologies have emerged as an essential component in reducing the overall carbon footprint of cement manufacturing [3].

Among the various carbon capture approaches, post-combustion CO_2 capture is particularly attractive for cement plants due to its compatibility with existing production processes. Cement kiln flue gas typically contains a relatively high concentration of CO_2 compared to power plant exhausts, which enhances the potential efficiency of capture technologies. However, the presence of impurities such as dust, nitrogen oxides, sulfur oxides, and water vapor poses additional challenges to the capture process and influences solvent performance and operational stability [4-5].

Chemical absorption using liquid solvents is one of the most established and commercially mature methods for post-combustion CO_2 capture. This technique relies on the reversible chemical reaction between CO_2 and an alkaline solvent, enabling selective separation of CO_2 from flue gas streams. Amine-based solvents, particularly monoethanolamine (MEA), have been widely studied and applied in industrial gas treatment due to their high reactivity with CO_2, fast absorption kinetics, and proven operational reliability. Despite these advantages, the large-scale application of chemical absorption in the cement industry is constrained by high energy requirements for solvent regeneration, solvent degradation, and increased operational costs.

Several studies have investigated the application of chemical absorption systems for CO_2 capture in power generation and natural gas processing; however, fewer studies have focused specifically on cement kiln flue gas, which exhibits distinct characteristics such as higher CO_2 concentration and variable gas composition. Understanding the interaction between flue gas properties, solvent behavior, and operating conditions is therefore essential for assessing the feasibility of chemical absorption in cement manufacturing. Moreover, evaluating the performance of amine-based CO_2 capture systems under cement-specific conditions is critical for identifying operational challenges and potential efficiency improvements.

In this context, the present study investigates CO_2 capture from cement kiln flue gas using chemical absorption with monoethanolamine as the absorbent. The study focuses on assessing CO_2 removal performance and examining the influence of key operational parameters on capture efficiency and energy demand. By addressing cement-specific flue gas conditions, this work aims to provide insights into the applicability of chemical absorption as a practical CO_2 mitigation strategy for the cement industry.

II. MATERIALS AND METHODS

2.1 Materials

Monoethanolamine (MEA, analytical grade, ≥99% purity) was used as the chemical absorbent for CO_2 capture without further purification. Deionized water was employed for preparing aqueous MEA solutions of the desired concentrations. A simulated cement kiln flue gas mixture was considered, composed primarily of carbon dioxide, nitrogen, oxygen, and water vapor, reflecting typical cement kiln exhaust conditions. Trace acidic impurities such as sulfur dioxide and nitrogen oxides were assumed to be present at low concentrations, consistent with post-dedusting cement plant flue gas.

Steam required for solvent regeneration was assumed to be supplied externally, representing low-pressure saturated steam typically available in industrial settings. Cooling water was used for solvent cooling prior to absorption and for condensation during the regeneration stage.

2.2 Chemical Absorption Procedure

CO_2 capture was carried out using a chemical absorption process based on reversible reactions between CO_2 and aqueous MEA solution. The absorption step involved intimate gas–liquid contact under counter-current flow conditions to enhance mass transfer and reaction efficiency. Lean MEA solution was introduced at the top of the absorber, while the flue gas stream entered from the bottom, allowing effective CO_2 uptake along the contact zone [6].

The rich solvent exiting the absorber, containing absorbed CO_2, was directed to the regeneration step. Prior to regeneration, heat exchange between rich and lean solvent streams was considered to improve thermal efficiency. Regeneration was conducted by heating the CO_2-rich MEA solution, leading to the release of absorbed CO_2 and restoration of solvent absorption capacity.

2.3 Operating Conditions

Aqueous MEA solutions with concentrations ranging from 20 to 40 wt% were evaluated to examine the effect of solvent strength on CO_2 capture performance. The absorption process was carried out at temperatures close to 40 °C, representative of cooled flue gas conditions, while regeneration was performed at elevated temperatures typical of amine stripping processes [7]. The solvent circulation rate was adjusted to achieve effective gas–liquid contact and target CO_2 removal efficiencies.

2.4 Performance Evaluation

The performance of the chemical absorption process was evaluated based on:

- CO_2 removal efficiency, calculated from the difference between inlet and outlet CO_2 concentrations in the gas stream.
- Solvent loading, expressed as moles of CO_2 absorbed per mole of MEA.
- Energy requirement for solvent regeneration, assessed in terms of thermal energy input during the desorption step.

These parameters were used to assess the feasibility and effectiveness of chemical absorption for CO_2 capture from cement kiln flue gas.

2.5 Data Analysis

All experimental and process data were analyzed to identify trends relating operating conditions to CO_2 capture efficiency and energy demand. Comparative evaluation was performed to determine the influence of solvent concentration and operating temperature on overall process performance. The results were interpreted with reference to the specific characteristics of cement kiln flue gas and industrial applicability.

The cement kiln flue gas stream was characterized by a relatively high CO_2 concentration compared to conventional power plant exhausts. The gas temperature was reduced to near-ambient conditions before contact with the solvent to ensure effective absorption. The gas pressure was maintained close to atmospheric conditions throughout the absorption process [8]. These conditions represent realistic post-conditioning scenarios in cement manufacturing facilities.

III. RESULTS AND DISCUSSION

3.1 CO_2 Removal Efficiency

The chemical absorption process using aqueous monoethanolamine demonstrated high CO_2 removal efficiency under cement kiln flue gas conditions. At an MEA concentration of 20 wt%, the CO_2 removal efficiency ranged between 68–75%, indicating limited absorption capacity at lower solvent strength. Increasing the MEA concentration to 30 wt% significantly improved capture performance, achieving CO_2 removal efficiencies of 85–90% under similar operating conditions. A further increase to 40 wt% MEA resulted in only marginal improvement, with removal efficiencies approaching 90–93%, suggesting diminishing returns at higher solvent concentrations.

The observed trend is attributed to the increased availability of reactive amine groups at higher MEA concentrations, which enhances the rate of CO_2 absorption. However, at elevated concentrations, increased solution viscosity and mass transfer resistance likely limit further improvement in capture efficiency. These results indicate that 30 wt% MEA provides an optimal balance between absorption performance and solvent handling characteristics for cement kiln applications [9].

3.2 Effect of Gas–Liquid Contact Conditions

Gas–liquid contact conditions played a crucial role in determining CO_2 capture performance. At lower solvent circulation rates, insufficient contact between the flue gas and MEA solution resulted in incomplete CO_2 absorption, with removal efficiencies below 80%. Increasing the liquid-to-gas ratio improved CO_2 uptake, with removal efficiencies exceeding 88% at optimized flow conditions. Beyond this point, further increases in solvent circulation showed negligible improvement in CO_2 removal while increasing energy demand for solvent regeneration.

This behavior highlights the importance of optimizing solvent flow rate to maximize absorption efficiency without imposing unnecessary energy penalties. Effective gas–liquid contact was essential for achieving high capture efficiency, particularly given the relatively high CO_2 concentration in cement kiln flue gas [10].

3.3 Solvent Loading Behavior

Solvent loading, expressed as moles of CO_2 absorbed per mole of MEA, increased with solvent concentration and improved gas–liquid contact. At 20 wt% MEA, average rich solvent loadings were in the range of 0.35–0.40 mol CO_2/mol MEA, whereas 30 wt% MEA solutions achieved higher loadings of approximately 0.45–0.50 mol CO_2/mol MEA. For 40 wt% MEA, solvent loading showed only a slight increase, indicating saturation effects under the studied conditions.

The lean solvent loading after regeneration remained relatively stable, typically between 0.15–0.20 mol

CO_2/mol MEA, confirming effective solvent regeneration and consistent cyclic performance. The difference between rich and lean loadings directly influenced solvent circulation requirements and overall energy consumption [11-12].

3.4 Energy Requirement for Solvent Regeneration

The energy demand associated with solvent regeneration was a key performance indicator of the CO_2 capture process. For 20 wt% MEA, the specific regeneration energy requirement was estimated to be approximately 3.8–4.2 GJ per ton of CO_2 captured, primarily due to higher solvent circulation rates needed to achieve moderate capture efficiency. At 30 wt% MEA, the regeneration energy decreased to approximately 3.2–3.5 GJ/t CO_2, reflecting improved solvent utilization and higher CO_2 loading capacity [13-14].

In contrast, 40 wt% MEA solutions exhibited a slight increase in regeneration energy demand, reaching values of 3.6–3.9 GJ/t CO_2, likely due to increased sensible heat requirements and higher solution viscosity. These results indicate that excessively high solvent concentrations may negatively impact overall energy efficiency, despite marginal gains in capture performance [15].

IV. PROPOSED PROCESS FLOWSHEET

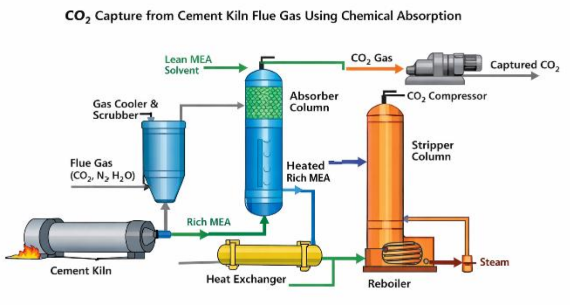

Figure 1: Process flow diagram for CO_2 capture using chemical absorption.

5. CONCLUSIONS

This study demonstrates that chemical absorption using monoethanolamine is an effective and technically feasible approach for capturing CO_2 from cement kiln flue gas. High CO_2 removal efficiencies were achieved under cement-specific flue gas conditions, with solvent concentration and gas–liquid contact playing a decisive role in process performance. An aqueous MEA concentration of around 30 wt% provided an optimal balance between CO_2 capture efficiency and solvent regeneration energy demand, achieving removal efficiencies above 85% while limiting excessive energy consumption. Although higher solvent concentrations offered marginal improvements in capture efficiency, they resulted in increased regeneration energy requirements, indicating diminishing returns. The results highlight that chemical absorption can be successfully applied to cement industry emissions, particularly due to the relatively high CO_2 content of kiln flue gas. However, the energy-intensive nature of solvent regeneration remains a key challenge, emphasizing the need for further integration with waste heat recovery and process optimization strategies.

REFERENCE

[1] Laribi, S., Dubois, L., De Weireld, G., & Thomas, D. (2019). Study of the post-combustion CO2 capture process by absorption-regeneration using amine solvents applied to cement plant flue gases with high CO2 contents. *International Journal of Greenhouse Gas Control*, *90*, 102799.

[2] Pan, L., Shi, W., Li, B., & Wei, X. (2021). Experimental investigation on the performance of [APMIm][NTf2] for capturing CO2 from flue gas of the cement kiln tail. *Journal of Thermal Science*, *30*(5), 1780-1788.

[3] Scholes, C. A., Ho, M. T., Aguiar, A. A., Wiley, D. E., Stevens, G. W., & Kentish, S. E. (2014). Membrane gas separation processes for CO2 capture from cement kiln flue gas. *International Journal of Greenhouse Gas Control*, *24*, 78-86.

[4] Dubois, L., & Thomas, D. (2018). Comparison of various configurations of the absorption-regeneration process using different solvents for the post-combustion CO2 capture applied to cement plant flue gases. *International Journal of Greenhouse Gas Control*, *69*, 20-35.

[5] Bosoaga, A., Masek, O., & Oakey, J. E. (2009). CO2 capture technologies for cement industry. *Energy procedia*, *1*(1), 133-140.

[6] Raksajati, A., Ho, M. T., & Wiley, D. E. (2013). Reducing the cost of CO2 capture from flue gases using aqueous chemical absorption. *Industrial & Engineering Chemistry Research*, *52*(47), 16887-16901.

[7] Barker, D. J., Turner, S. A., Napier-Moore, P. A., Clark, M., & Davison, J. E. (2009). CO2 capture in the cement industry. *Energy procedia*, *1*(1), 87-94.

[8] Romeo, L. M., Catalina, D., Lisbona, P., Lara, Y., & Martínez, A. (2011). Reduction of greenhouse gas emissions by integration of cement plants, power plants, and CO2 capture systems. *Greenhouse Gases: Science and Technology*, *1*(1), 72-82.

[9] Vatopoulos, K., & Tzimas, E. (2012). Assessment of CO2 capture technologies in cement manufacturing process. *Journal of cleaner production*, *32*, 251-261.

[10] Antzaras, A. N., Papalas, T., Heracleous, E., & Kouris, C. (2023). Techno–economic and environmental assessment of CO2 capture technologies in the cement industry. *Journal of Cleaner Production*, *428*, 139330.

[11] WANG, Y., CHEN, Z., CUI, S., YANG, J., & PEI, T. (2025). Research Progress on CO 2 Capture in Cement Kiln Flue Gas and Modification of Absorption Efficiency of Calcium Carbide Slag. *Journal of the Chinese Ceramic Society*, *53*(5), 1258-1268.

[12] Fang, M., Yi, N., Di, W., Wang, T., & Wang, Q. (2020). Emission and control of flue gas pollutants in CO2 chemical absorption system–A review. *International Journal of Greenhouse Gas Control*, *93*, 102904.

[13] Thitakamol, B., Veawab, A., & Aroonwilas, A. (2007). Environmental impacts of absorption-based CO2 capture unit for post-combustion treatment of flue gas from coal-fired power plant. *International Journal of Greenhouse Gas Control*, *1*(3), 318-342.

[14] Vega, F., Cano, M., Gallego, L. M., Camino, S., Camino, J. A., & Navarrete, B. (2017). Evaluation of MEA 5 M performance at different CO2 concentrations of flue gas tested at a CO2 capture lab-scale plant. *Energy Procedia*, *114*, 6222-6228.

[15] Shamsi, M., Naeiji, E., Vaziri, M., Moghaddas, S., Elyasi Gomari, K., Naseri, M., & Bonyadi, M. (2025). Optimization of energy requirements and 4E analysis for an integrated post-combustion CO2 capture utilizing MEA solvent from a cement plant flue gas. *Environment, Development and Sustainability*, *27*(4), 9379-9405.